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Overview of geologic and geohydrologic conditions at the Finnsjön site and its surroundings

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SUMMARY

The geologic and tectonic conditions of the Finnsjön site and its surroundings have been studied on several scales ranging from regional to site scale. The Finnsjön study site is situated within a 50 km^2 shear lens. This lens is a part of a regional, c. 20–30 km wide, WNW trending shear belt that was developed 1 600 – 1 800 million years ago. The final repository for reactor waste (SFR) at Forsmark is also situated within this shear belt.

The Finnsjön Rock Block, bounded by regional and semi–regional fracture zones, constitute the main part of the Finnsjön site. The size of the block is about 6 km^2. A northeasterly trending fracture zone, Zone 1, divides this block into two lower order blocks, the northern and the southern block.

In general, interpreted fracture zones, as well as the rock mass in general, are far better known in the northern Finnsjön block compared to the southern block. This is due to extensive and detailed investigations of a gently dipping fracture zone, Zone 2, in the northern block.

A tectonic model including 14 fracture zones is suggested for the Finnsjön site and its surroundings. These zones have mainly been interpreted from lineament maps and to some extent from borehole measurements. The lack of borehole data implies that many of interpreted fracture zones, especially in the southern block and outside the Finnsjön site, should be regarded as tentative.

The good general knowledge of the geologic and geohydrologic conditions in the northern Finnsjön block, and possible stagnant groundwater conditions below Zone 2, makes the northern block the most suitable location for the generic repository at the Finnsjön site.

CONTENTS

1. INTRODUCTION

The objective of this report is to present main geologic and tectonic characteristics of the Finnsjön site and its surroundings. To some extent also data concerning the rock mechanical, thermal and hydraulic properties are presented. This report is one of several reports intended to provide the data needed for a safety assessment (SKB-91) of a generic repository at the Finnsjön site.

The Finnsjön site is located in central Sweden, about 140 km north of Stockholm (Figure 1). The site has a flat topography with differences in altitude of less than 15 m. Although outcrops are common, the area is covered to 85% by Quaternary sediments, mainly moraine.

The Finnsjön site was investigated mainly from 1977–1978 to assess its suitability to host a repository for reprocessed nuclear waste; ancillary studies continued at the site until 1982. This investigation included 8 cored boreholes, down to 700 m depth, and extensive borehole geophysical, geochemical and hydraulic measurements. During 1985, a detailed study started regarding the geologic and hydraulic characteristics of a gently dipping fracture zone in the northern part of the site. This study has included the drilling of three cored boreholes and three percussion drilled boreholes. The main results are reported in Ahlbom and Smellie (eds, 1989). In Ekman (1989) all studies before 1989 in the Finnsjön region is presented.

The geologic and tectonic conditions of the Finnsjön site in this report are presented in three scales, Table 1 and Figure 1.

Table 1. Different working scales, name of areas and size of areas.

Scale	Area	Size
Regional	Northeastern Uppland	50 x 50 km^2
Semi-regional	Gåvastbo area	10 x 10 km^2
Site (local)	Finnsjön site	2 x 2.5 km^2

The lineament interpretations have mainly been based on topographical maps of different scales and resolutions. Lineament interpreted on the regional map might not be obvious on the semi-regional or site maps and vice versa. For example, an extensive and wide linear depression might be interpreted as a lineament on the regional scale but may not be detectable on maps of larger scales. In this report this is accommodated by transferring all interpreted lineaments on small-scale maps to the subsequent larger-scale maps.

The report is structured so that the regional and semi-regional geological settings is presented in Chapters 2 and 3. Chapter 4 presents the main characteristics of the Finnsjön site regarding geologic and tectonic conditions, as well as some physical, hydraulical and mechanical conditions and properties. The isostatic depression/uplift of the Finnsjön region during the last glaciation and related sea levels changes is discussed in Chapter 5, together with a discussion regarding the occurrence of saline groundwater. The Chapter 6 presents interpreted fracture zones at the Finnsjön site and its surroundings followed by a summarizing discussion in Chapter 7.

This report is an updated and reworked version of the SKB status report AR 89-08 (Ahlbom and Tirén, 1989). Changes have been made in the report format, some fracture zones have been added and the characteristics of some fracture zone (width, dip) have been modified. Also, a chapter concerning the distribution of saline groundwater within the Finnsjön site and its surroundings has been included.

2. REGIONAL GEOLOGY - NORTHEASTERN UPPLAND

2.1 Geologic history - northeastern Uppland

The rocks comprising the bedrock of northern Uppland are between 2,200 to 1,600 million years old. The oldest rock are deposited at the surface of the crust (supracrustal rocks) and comprises acid volcanics (leptites) and metasediments with intercalated mineralized beds (eg. Dannemora Iron Mine). A basement, on which these rocks were deposited, has not been identified.

The supracrustal rocks were later deformed and altered during a period of mountain building, the Svecokarelian orogeny, which culminated c. 1,850 million years ago. Huge amounts of granitoids, a magmatic suite of gabbroic to granodioritic (youngest) rocks, were at this time emplaced in the supracrustal sequence. The culmination of the ductile deformation during the Svecokarelian orogeny occurred just after the intrusion of the granitoids. The deformation resulted in a regional foliation and shearing along contacts of major lithological boundaries. The mineralogy of the bedrock indicate that this deformation occurred at a temperature of c. 400-600 °C and a pressure of c. 4-8 kbar (middle amphibolite facies).

The deformation ceased, but before the deformation changed character from ductile to semi-ductile the bedrock was intruded by dolorite dykes (c. 1,800 million years ago), and the deformation become more linked to regional shear zones, forming regional lens-shaped (anastomosing) patterns. These shear zones have a N-S trend in central Uppland while they form a c. 20-30 km wide, WNW trending belt along the northeastern coastline of Uppland. The Singö fault (section 2.3) is interpreted as a major shear zone within this belt.

After the culmination of the semi–ductile deformation, emplacements of reddish to greyish–red granites occurred, c. 1,700 million years ago. These granites overprinted the semi–ductile shear pattern and brecciated the bedrock. The bedrock was affected by thermal alteration and deformation at the contacts to the late granites. The deformation was locally intensive.

Younger intrusive rocks, younger than 1,700 million years old, have not been recognized in this area. However, the record of younger doleritic and alkaline intrusions just outside this area are numerous. This indicate that the region was affected by block faulting during a long period, more than 800 million years. This block faulting declined and erosion resulted in the formation of the sub–Cambrian peneplain for more than 600 million years ago. A sequence of Cambro–Silurian sediments were deposited on the peneplained surface, which was distorted by minor faulting. The sediments are now eroded away, except for some few remnants, and the present ground surface of northern Uppland coincide roughly with the sub–Cambrian peneplain.

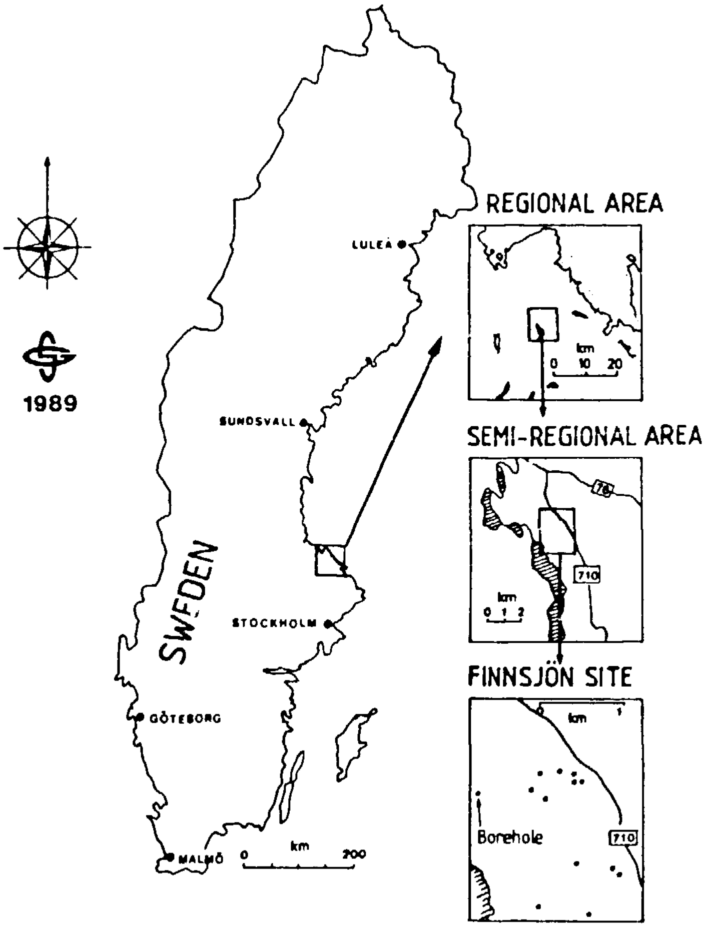

Figure 1. Location of regional area (northeastern Uppland), semi–regional area (Gåvastbo area), and Finnsjön site (local area).

2.2 Bedrock - northeastern Uppland

A generalized map showing the rock distribution in a 50x50 km^2 regional area, with the Finnsjön site in its centre, is presented in Figure 2.
The oldest rocks, the 2,200–1,850 million years old meta-volcanics and meta-sediments (supracrustals), occur along regional shear zones or downfolded in tight synformal structures. These rocks have irregular boundaries and constitute c. 25% of the bedrock.

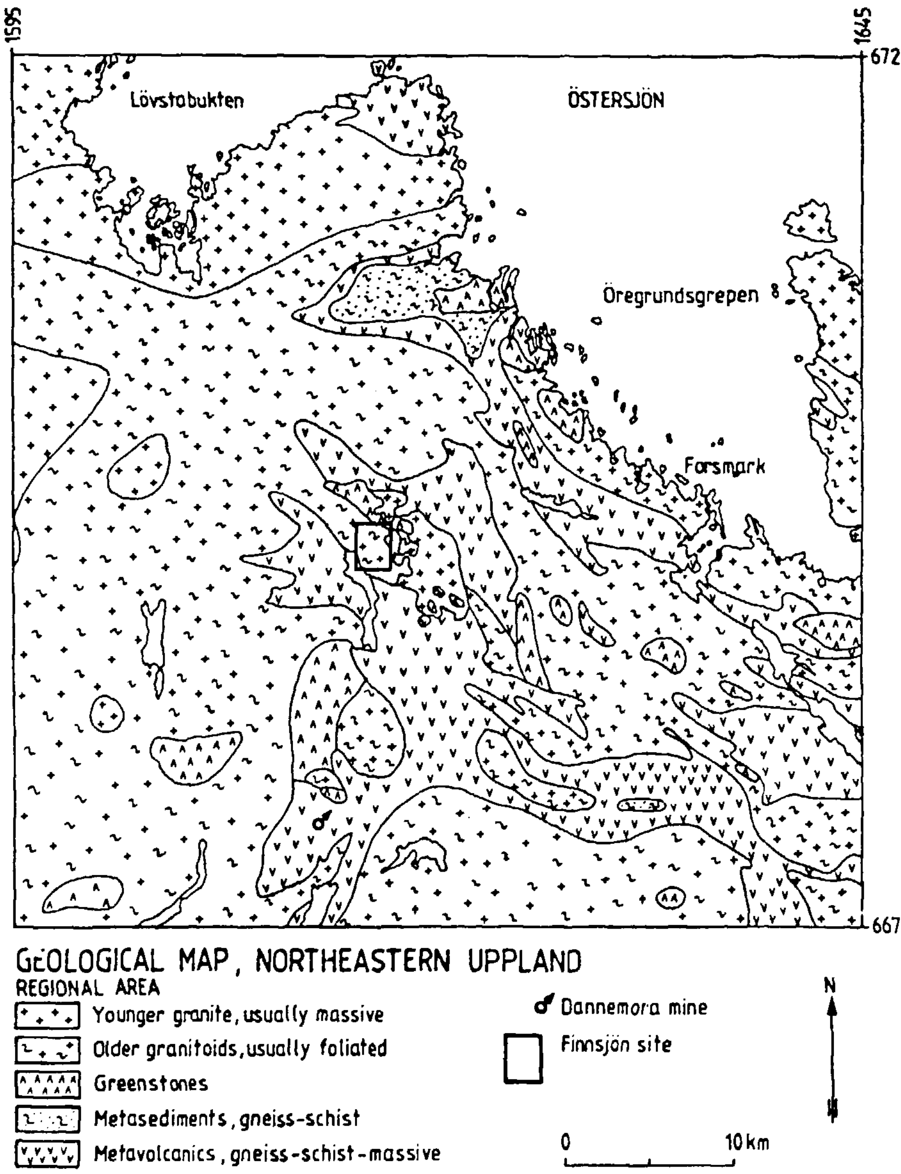

Figure 2. Geology of northeastern Uppland, regional area (modified from Söderholm et al., 1983).

Notable is the pronounced NW–SE orientations of these rocks in the northern part of the map, i.e. parallel to the Singö fault. At the Dannemora Mine these old supracrustals are downfolded to great depths, c. 500 m in the southern part of the mine to more than 1100 m north of the mine, along a N30E fold axis plunging gently northwestward. The folding is argued to be caused by the intruding Svecokarelian granitoids (c. 1,850 million years old).

More than 50% of the present bedrock consist of major intrusions of granodiorite–granitic rocks of Svecokarelian age. These granitoids deformed earlier intruded basic rocks. The penetrative deformation during the Svecokarelian orogeny uniformed the structure of the bedrock, giving the granitoid rocks a shear gneiss character on a regional scale. The Finnsjön site is located within a granodioritic intrusion.

Large intrusions of younger granites (post–Svecokarelian, c. 1,700 million years), occur preferable in the northern part of the map. These are accompanied by pegmatite and aplite dykes.

2.3 Lineaments - northeastern Uppland

The lineaments in the regional area have been interpreted from an altitude map in scale 1:250 000 with contour lines drawn for every 12.5 m (Carlsson and Gidlund, 1983). Within this region the altitude changes from sea level and to a maximum altitude of 62 m. The relief reflects the surface of the bedrock since the thickness of the Quaternary cover (mainly moraine and clay) for most areas is not more than a few metres thick. The direction of the movement of the last inland ice was predominately toward the south. The interpreted lineaments are presented in Figure 3.

The lineaments are in general curved, forming a network of linsoidal blocks. At least two sets of lineaments are present, one trending north to northeast and the other with a northwesterly trend. The linsoidal shape of the rock blocks indicate that the lineaments reflect shear structures. It is not clarified if these two shear sets have been active at the same time, forming a conjugate shear configuration.

An interesting feature of this region is the systematic tilting of major blocks (up to 2 degrees), as indicated in Figure 3. The ground surface of the north-northeast trending rock blocks are tilted towards the east and southeast while the ground surface of northwest trending rock blocks dips towards the north-east. The tilting is interpreted to be caused by listric faults (spoon shaped). Close to the ground surface these faults are probably steeply dipping.

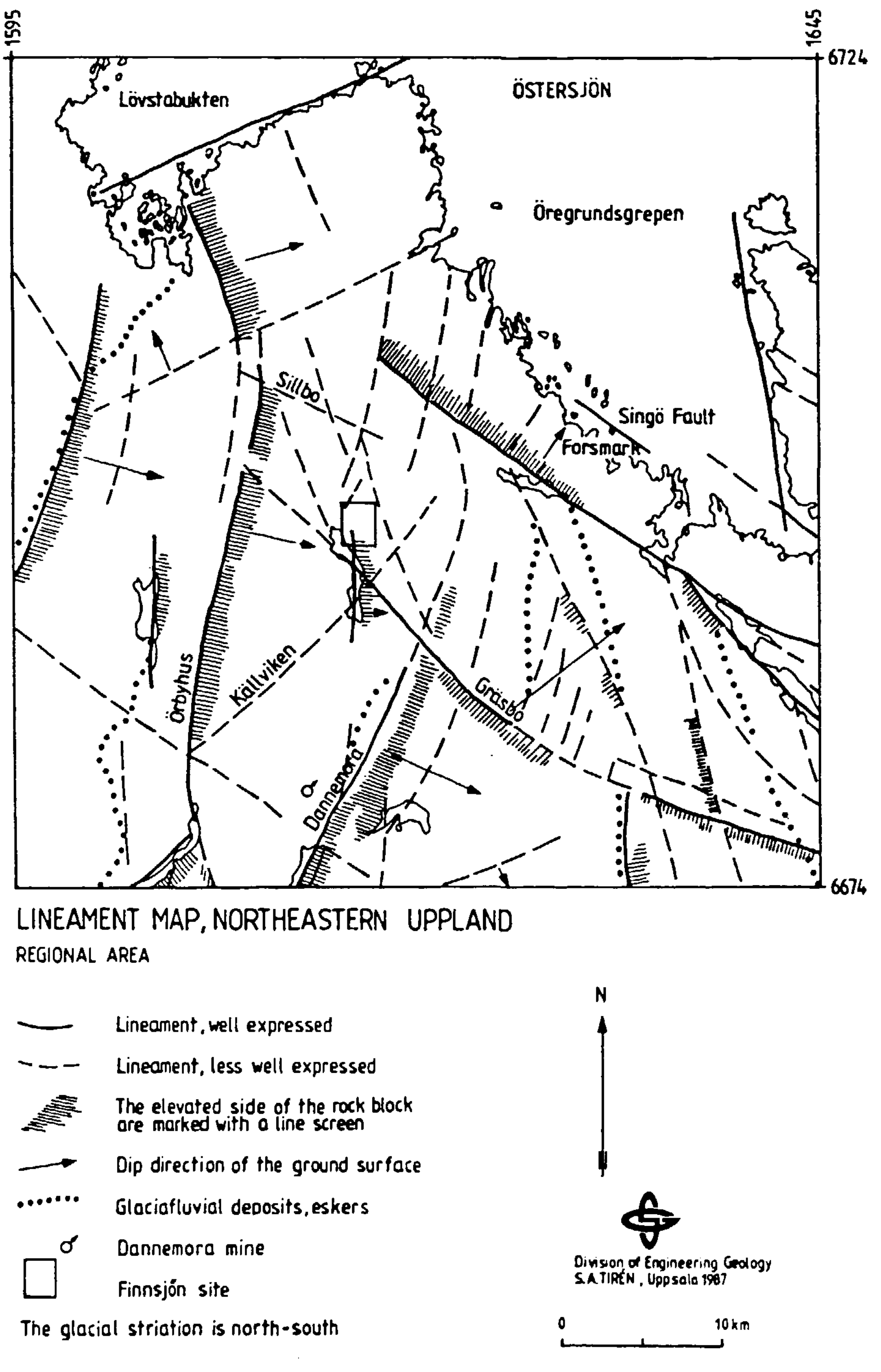

Figure 3. Lineament map of northeastern Uppland, regional area.

Only one of the lineaments on the regional map has been investigated in detail. This is the northwesterly trending Singö fault, Figure 3. This fault has been studied in connection with the construction of the final repository for reactor waste (SFR) at Forsmark (SFR1, 1987). At this location the fault is 100–200 m wide and subvertical. The zone exhibit a complex tectonic structure with about c. 100 m of altered and mylonitized bedrock and c. 15 m of crushed bedrock in the central part of the fault. The hydraulic conductivity, estimated from borehole tests, varies strongly between different boreholes. In the central (core) part of the fault the average conductivity value is $4 \cdot 10^{-6}$ m/s, while the conductivity in the peripheral part is $5 \cdot 10^{-7}$ m/s (SFR1, 1987).

3. SEMI-REGIONAL GEOLOGY - GÅVASTBO AREA

3.1 Bedrock - Gåvastbo area

The geology revealed on a semi-regional scale (Gåvastbo area, 10x10 km^2) is presented in Figure 4. The Finnsjön site is situated in the western wedge of a NW-trending regional shear lens. The shear lens is enveloped by foliated supracrustal rocks. The central part of the lens, containing the Finnsjön site, is composed of a sequence of rocks from Svecokarelian (c. 1,800 million years old) gabbro and granodiorite to young (c. 1,700 million years old) granite. The contacts between these rock types are complex, interfingering each other. Most probably this complexity reflects not only primary rock boundary configuration but also the tectonic distortion of the bedrock (faults). Examples of the latter are the WNW-boundary between the gabbro and the granodiorite in the northeastern part of the map and the contact between the granodiorite and the young granite in the central part.

The main trend of the foliation in the supracrustal rocks in the northern part of the area is conform with the northwesterly orientation of the regional shear lens.

The regional foliation in the southeastern part of the map has a divergent orientation, trending E–W. The two regions are divided by a NW-trending fault (section 3.2), which branches in its western part. This regional fault follows a c. 1.5 km wide shear zone with foliation oriented parallel to the zone.

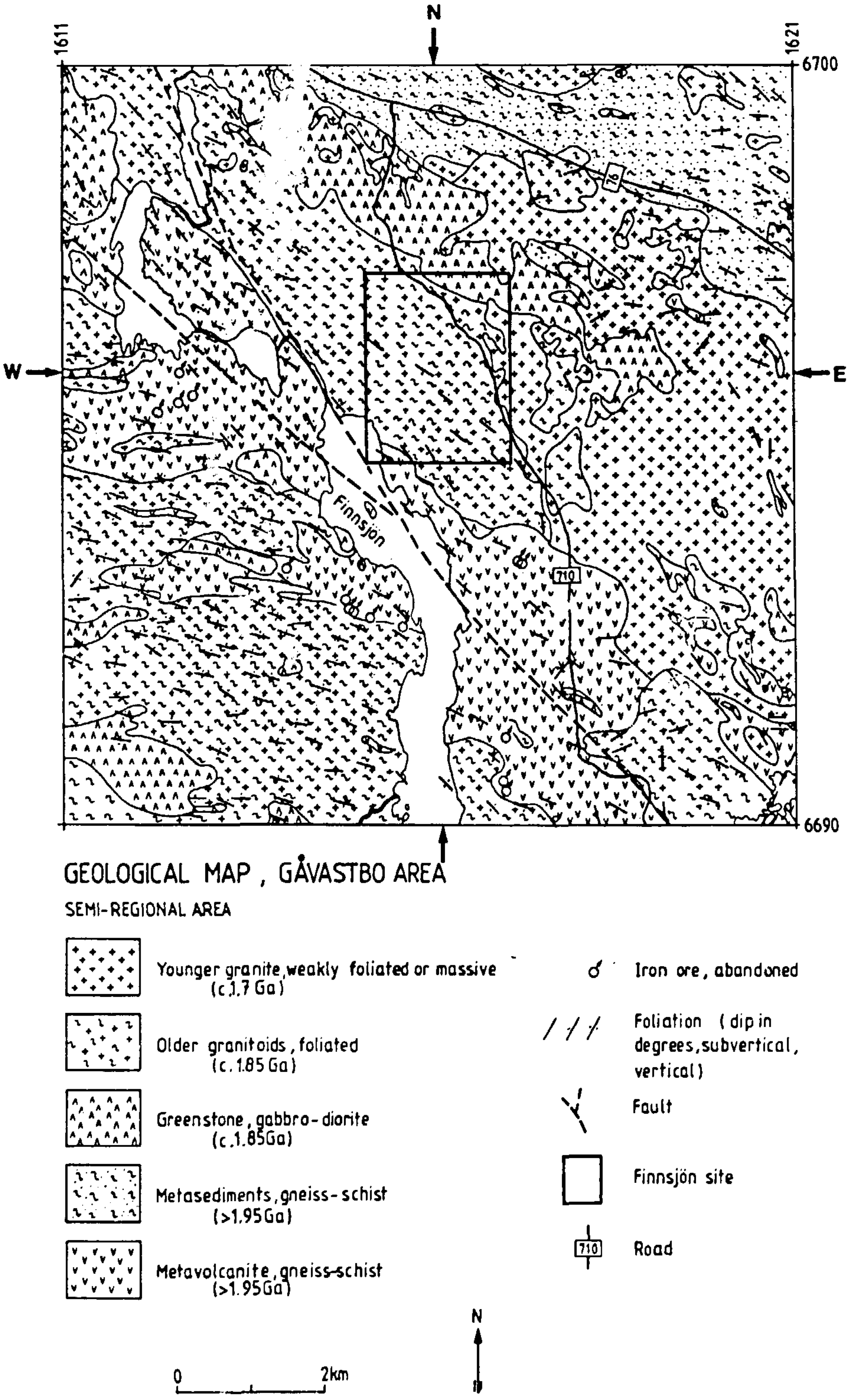

Figure 4. Geology of the Gåvastbo area. Location of the geological cross-sections in Figure 7 are marked by arrows (modified from Stålhös, 1988).

3.2 Rock blocks - Gåvastbo area

The lineament interpretation on the semi-regional scale is carried out on a 1:50 000 topographical map contoured every 5 m. The studied area is 10 x 10 km. The map of rock blocks in the Gåvastbo area is presented in Figure 5. A subdivision of rock blocks boundaries into different orders is presented in Figure 6. The lineaments interpreted on the regional scale map has been transferred to the map of rock blocks in the semi-regional scale.

Extensive regional lineament occur in the semi-regional area. One of these lineaments occur in the southwestern part of the area and has an orientation (northwest) and character (anastomosing) similar to the Singö fault.

Other lineaments transferred from the regional scale lineament map are north or northeast trending. These occur in the western (lake Finnsjön) and northern part of the semi-regional area. The regional lineaments are in the semi-regional scale often expressed as trains of minor lineaments.

The lineaments on the semi-regional scale map occur predominantly in three directions, N-S, NW and NE. Two tentative geologic vertical cross-sections, N-S and E-W, across the Gåvastbo area is presented in Figure 7. The location of the cross-sections is marked in Figure 5.

3.3 Tentative rock block model

A simplified and generalized rock block model of the Finnsjön region is presented in Figure 8. In this model all lineaments are interpreted as fracture zones. The extensive and curved lineaments, trending northwest and northeast, in the regional and semi-regional scales are interpreted as shear zones. No interpretation of the genesis of the north-south lineaments is made.

In the model the regional northwest trending shear zones, forms a major shear lens (a highest order structure). Minor NW-trending shear zones, conformed to the regional shear zones, occur within the lens. The lens is intersected by northeast trending and extensive shear zones and less extensive N-S fracture zones. These three sets of fracture zones results in rock blocks of prismatic shapes. The Finnsjön site is situated in one of these blocks, the Finnsjön Rock Block, in the western wedge of the regional shear lens.

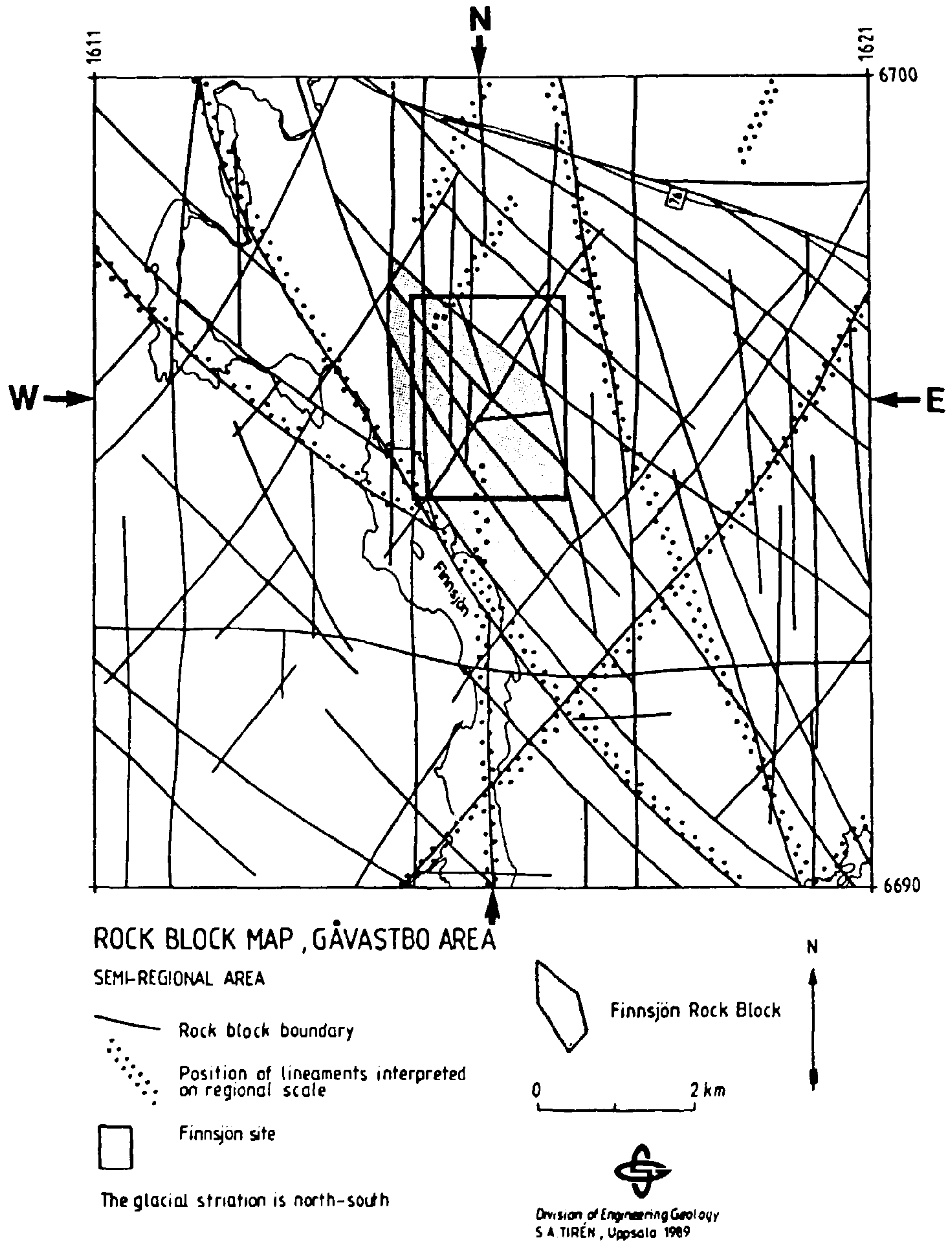

Figure 5. Rock block map of the Gåvastbo area, semi-regional area. Location of the geological cross-sections in Figure 7 are marked by arrows.

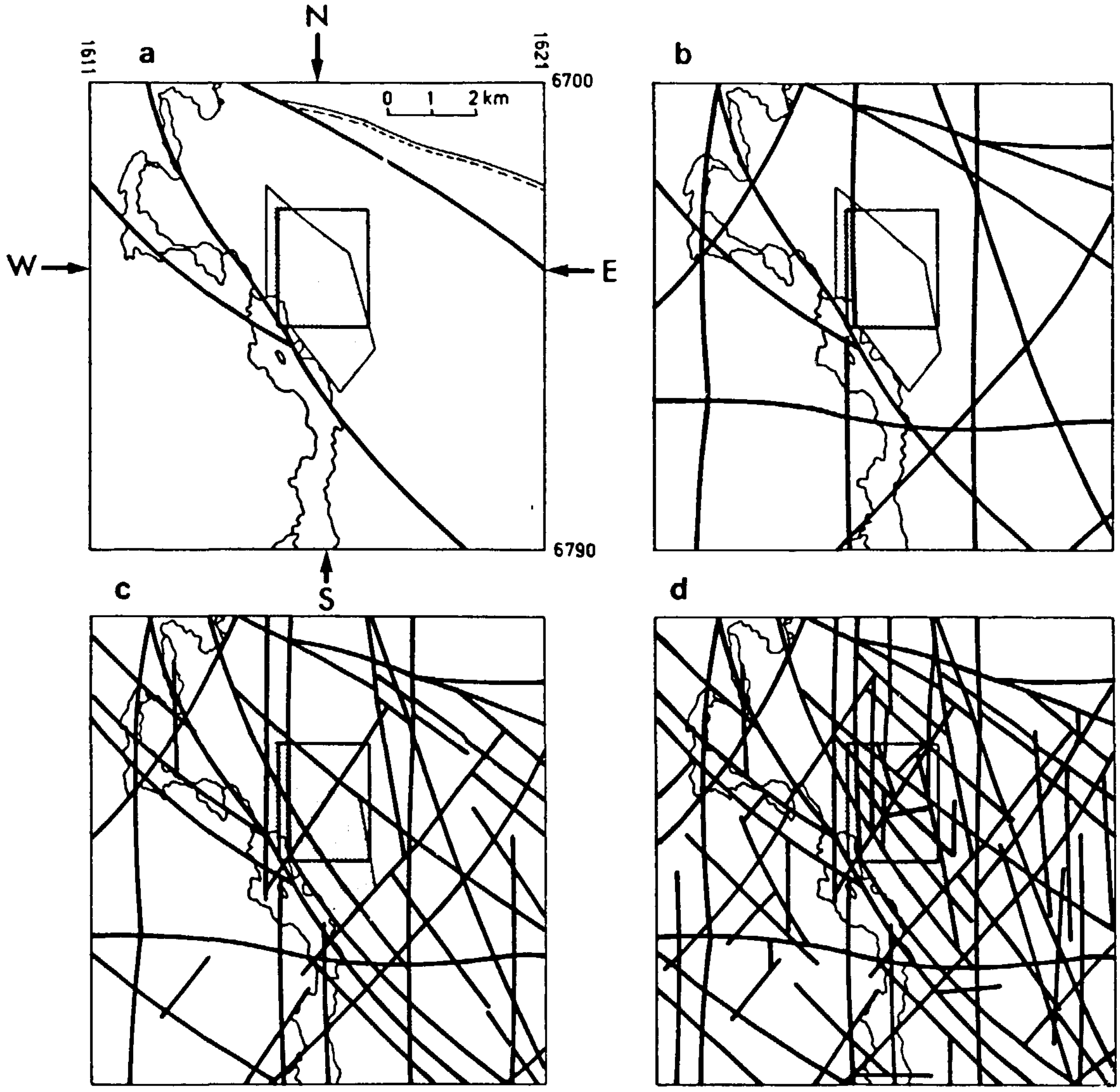

Figure 6. Four orders of rock block boundaries in the Gåvastbo area.: a. first order structures, b. with second order structures added, c. third order added and d. all four order structures compiled.

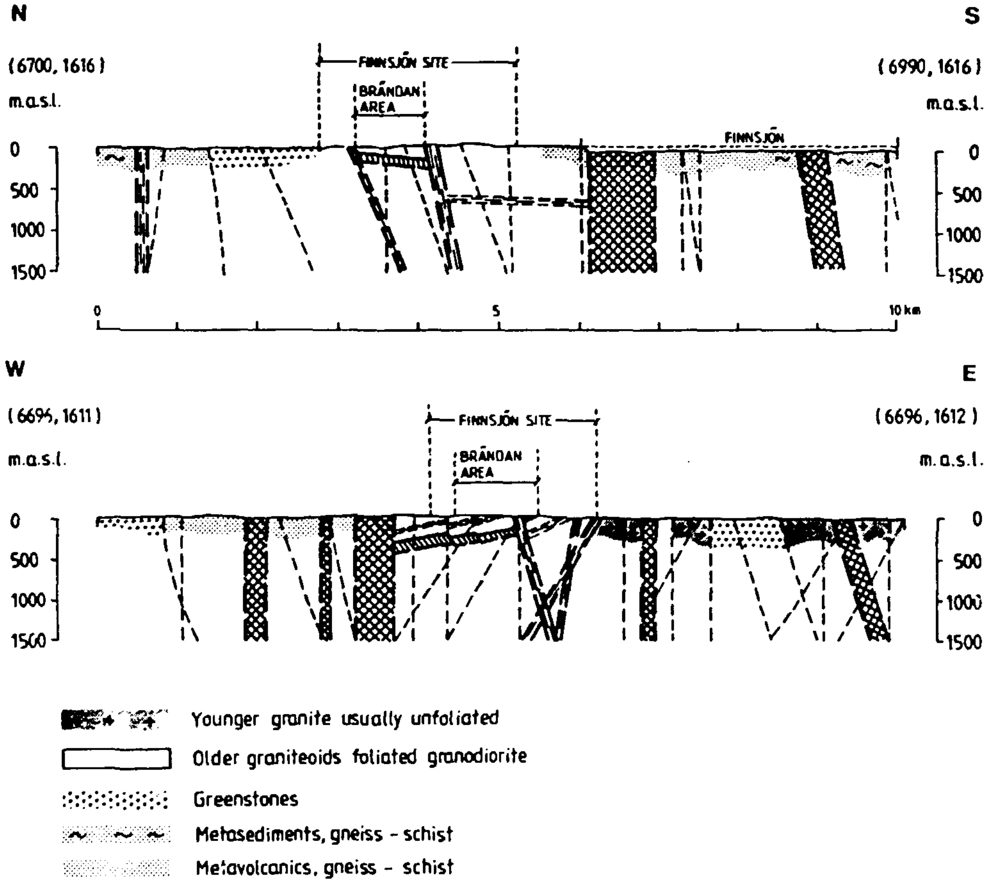

Figure 7. Vertical geological cross-sections in N-S and E-W through the Gåvastbo area. Arrows mark lineaments identified on the regional map. Legend of rock types is presented in Figure 4.

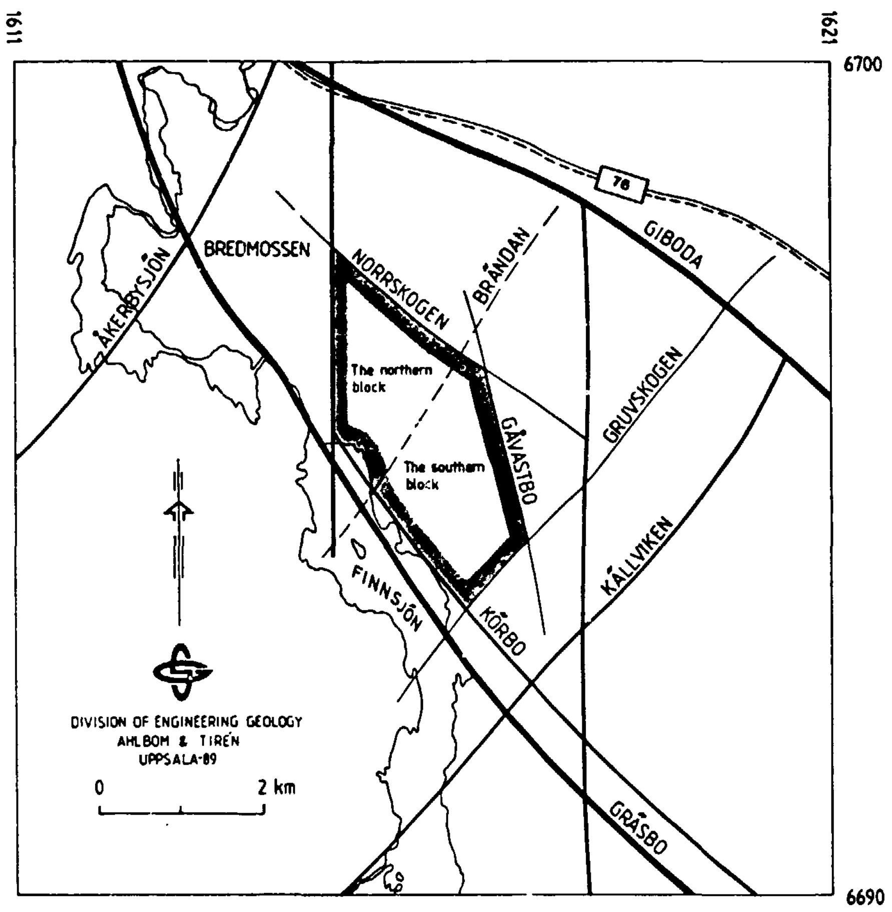

Figure 8. The Finnsjön Rock Block (rastered area). The Brändan fracture zone divides the Finnsjön Rock Block into the second order northern block and southern block.

4. THE FINNSJÖN SITE - MAIN CHARACTERISTICS

4.1 General

The Finnsjön site has a flat topography with differences in altitude of less than 15 m. Although outcrops are common, the area is covered to 85% by Quaternary sediments, mainly moraine and peat.

Investigations for different purposes (chapter 1) have resulted in 11 cored boreholes, down to 200–700 m depth, and extensive borehole geophysical, geochemical and hydraulical measurements. In addition, there are a 16 shallow (c. 100 m) percussion borehole and two deep (288 and 459 m) percussion boreholes (cf. Figure 9).

4.2 Bedrock - Finnsjön site

Within the Finnsjön area the predominant rock is a greyish foliated granodiorite. Minor amount of pegmatite, metabasite and aplite also occur. The granodiorite is bordered to the east by a reddish young granite and to the northeast by a layered gabbro (Figure 4). Metavolcanic rocks occur to the west and to the south of the site.

Granodiorite

The granodiorite, which is greyish, medium grained and uniform within the Finnsjön site, was thoroughly deformed during the Svecokarelian orogeny (c. 1,800 millon years ago) and transformed into a gneiss. The gneissosity is defined by a parallel arrangement of minerals (hornblende and biotite) or mineral aggregates (flakes of recrystallized quartz). The orientation of the gneissosity is uniform, N50–60W/80–90NE. The foliation, character and colour of the granodiorite is locally changed due to mylonitization, cataclasis, and hydrothermal alteration (red colouring) along minor shear zones.

Metabasites

Basic rocks occur as minor elongated xenoliths and as inlayers in the granodiorite. The xenoliths (less than 23 cm in length) are of gabbroic affinity and are evenly distributed within the granodiorite.

Inlayers of basic rocks occur as dolerite dykes or as amphibolite sheets. The latter lying within shear zones. The dykes are some decimeters wide and cross-cut the foliation. The dykes are oriented N-S and E-W, but sheared dykes, metadolorites/amphibolites have a predominating WNW trend with a steep dip towards the south. The dolerite dykes are well welded to the country rock and have the same degree of fracturing as the country rock.

Pegmatite and aplite

Pegmatite and aplite occur as dykes cutting the gneissosity of the granodiorite at right angles. The aplite dykes are related to the late granite outside the Finnsjön site. They are pink, 0.1 –1.0 m wide, and often very extensive, locally mappable for more than 500. The common pegmatites are grey up to 0.2 m wide and traceable for some 10 m.

Two sets of aplite dykes occur; N40–60E/steep and subhorizontal with a dip towards the south. Fractures within these dykes are often slightly oblique to the trend of the dykes.

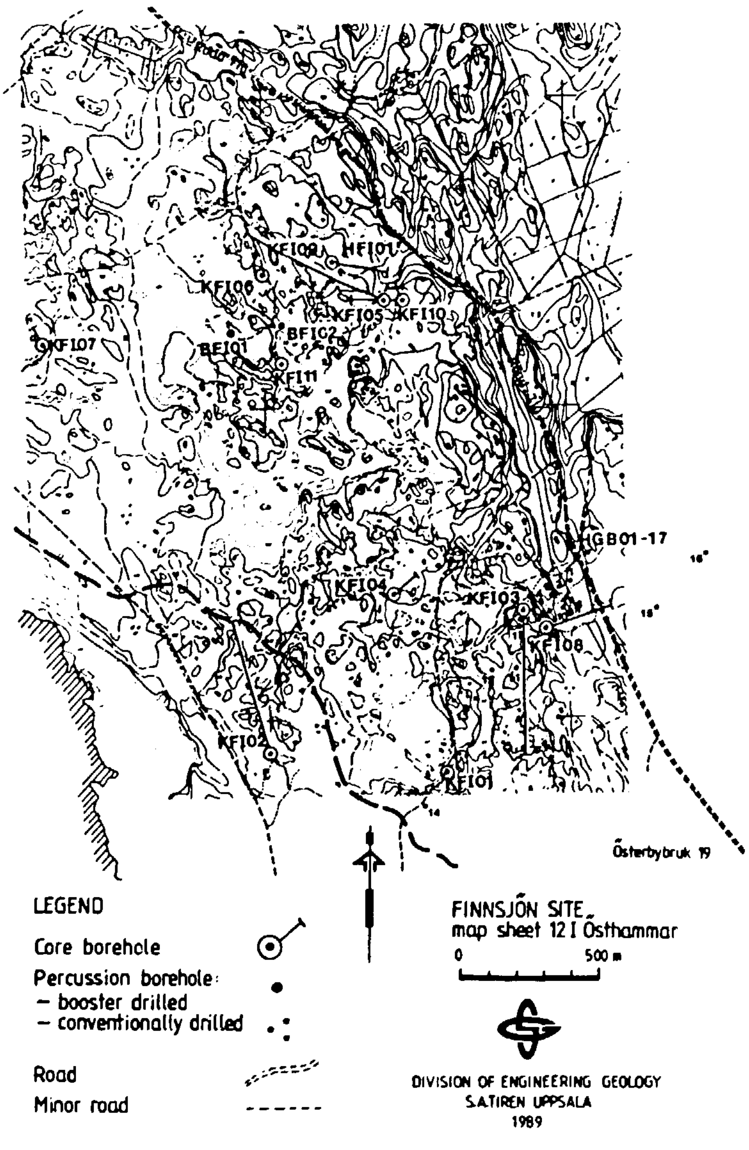

Figure 9. Borehole locations at the Finnsjön site.

4.3 Lineaments and rock blocks - Finnsjön site

The rock blocks shown in Figure 10 is based on a lineament interpretation of a detailed topographical map, 1:10 000, contoured every one meter. To confirm and complement the results from this study also lineament interpretation from aerial photos has been made (section 4.4).

A subdivision of rock blocks into different orders is presented in Figure 11. Tentative vertical cross-sections, N-S and E-W, showing a geological model of the Finnsjön site is presented in Figure 12. The locations of the cross-sections is shown in Figure 10.

Three main sets of lineaments occur in the Finnsjön area:

* North-south (N20E-N20W) lineaments
* Northwest (N50-60W) lineaments
* Northeast (N25-35E) lineaments

The most common and persistent lineaments are trending N-S and NW.

North-south lineaments

North-south lineaments are most pronounced in the western upper and eastern lower part of the area. The most prominent of these lineaments is the Gåvastbo lineament (G in Figure 10). This lineament constitute the eastern limit of the Finnsjön Rock Block.

Northwest lineaments

Minor northwest (N20W-N70W) lineaments occur throughout the Finnsjön Rock Block. Some of these lineaments are subparallel to the foliation of the granodiorite.

Northeast lineaments

The northeast lineaments occur frequently, but they are less persistent than lineaments of other sets. An exception is the Brändan fracture zone, N30E/75SE (B in Figure 10), which stands out as a marked lineament. The Brändan fracture zone (Zone 1) divides the Finnsjön Rock Block into a northern and a southern block. Two boreholes, KFI05 and KFI10, has been drilled through this zone.

Rock blocks

If the Finnsjön Rock Block, Figure 8, is considered as a first order block with a size of about 6 km^2, the northern and southern blocks, separated by the Brändan zone, would be second order blocks with sizes of about 2.7 and 3.3 km^2, respectively. Third order blocks are shown in Figure 10. A rough estimate of the average size of these blocks are 200 m x 100 m.

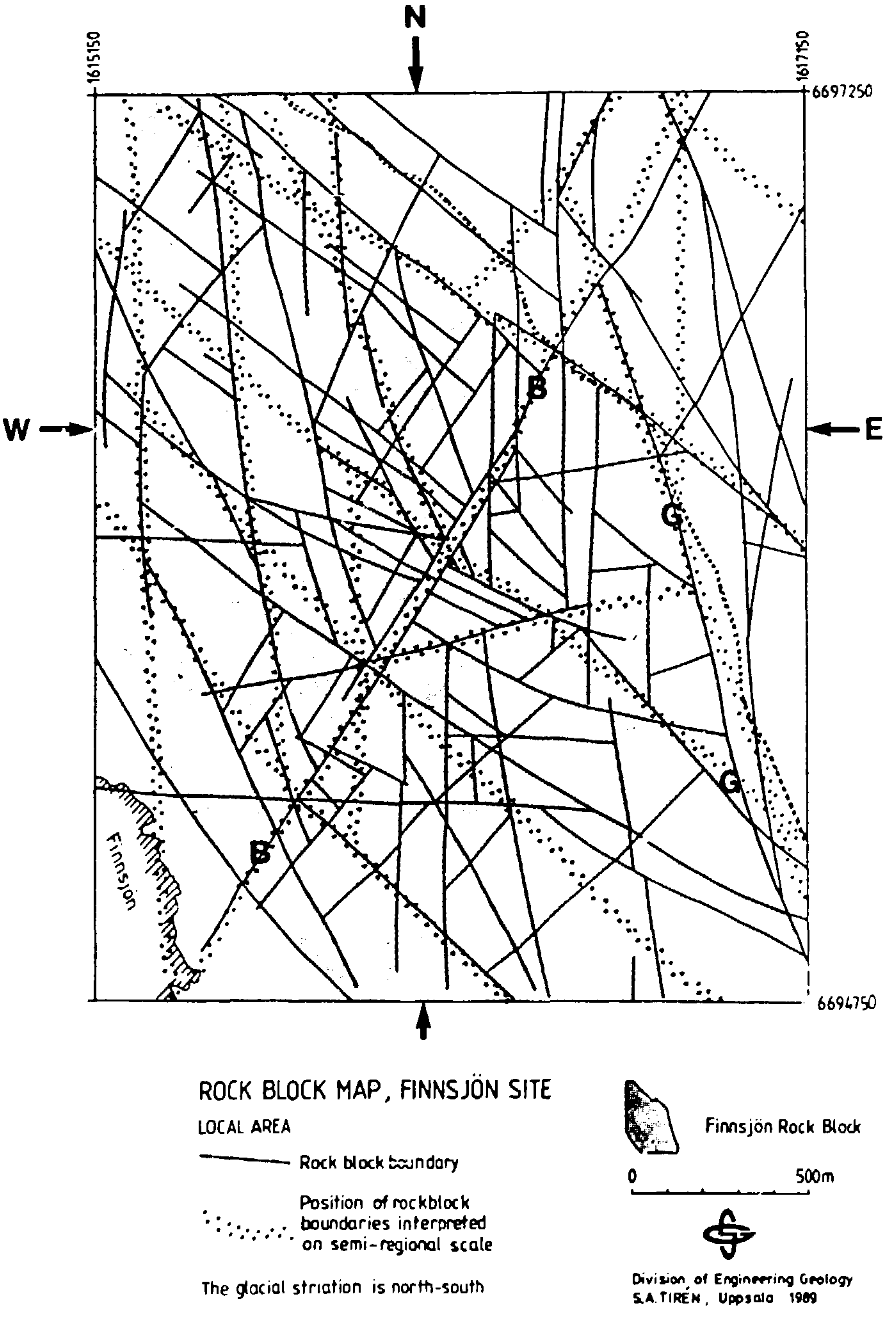

Figure 10. Rock block map of the Finnsjön site. Rastered area is a part of the Finnsjön Rock Block.

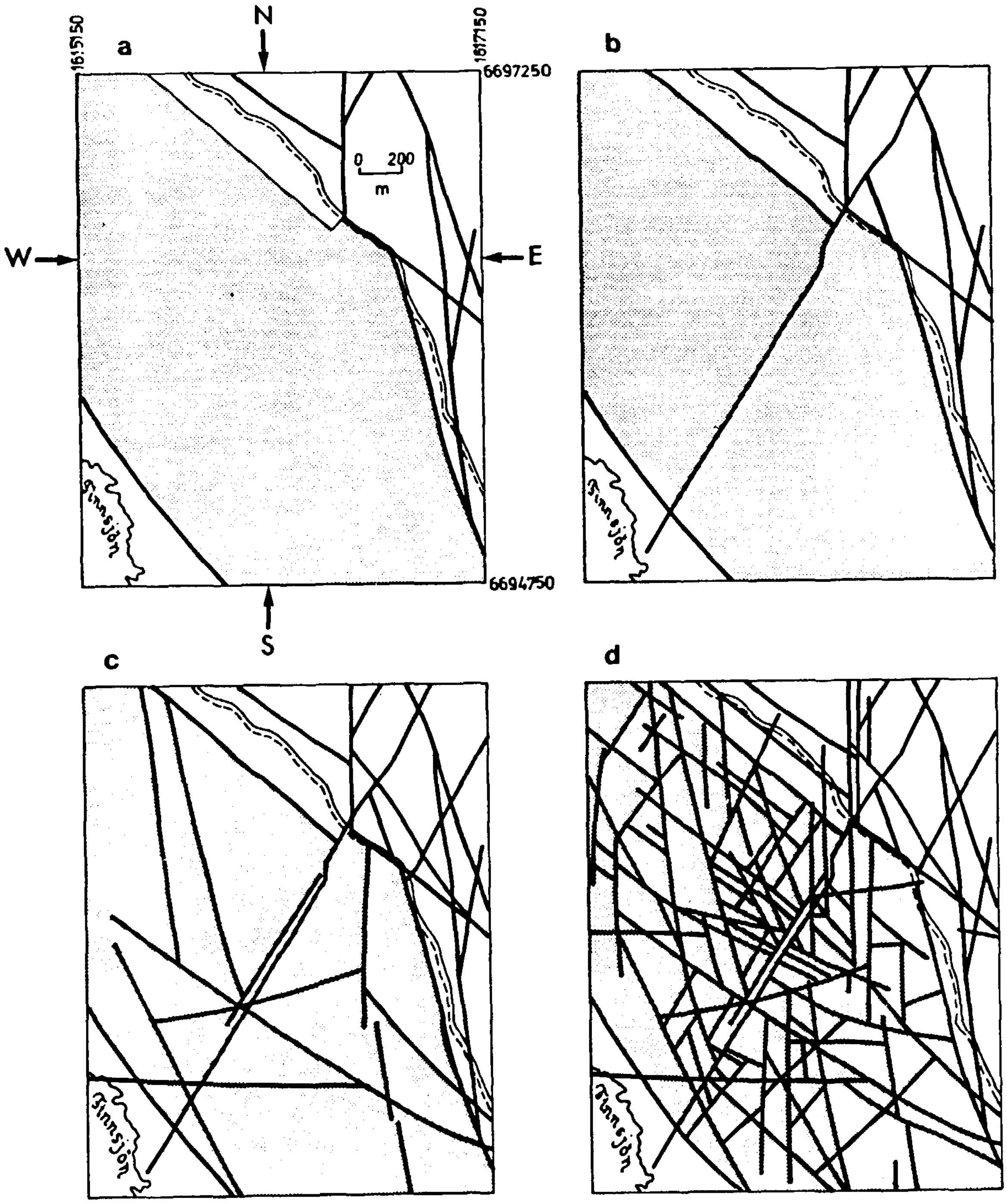

Figure 11. Four orders of rock block boundaries in the Finnsjön site.: a. first order structures, b. with second order structures added, c. third order added and d. all four order structures compiled.

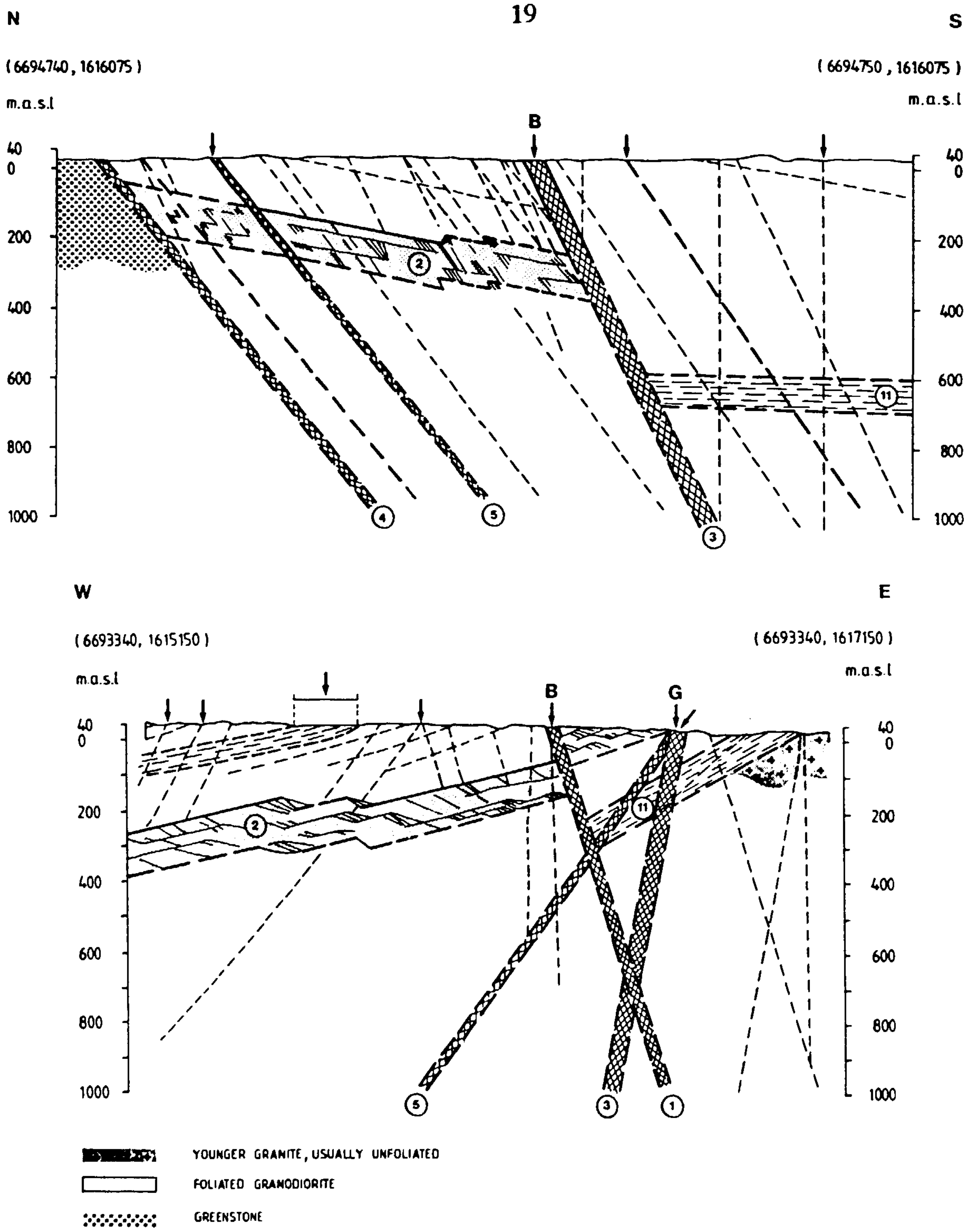

Figure 12. Tentative geological vertical cross-sections in N–S and E–W through the Finnsjön site. The numbers at fracture zones refer to their identification (c.f. Chapter 6). Arrows mark lineaments identified on the semi-regional scale map. Locations of cross-sections is shown in Figure 10.

4.4 Interpretation of main lineaments from aerial photos

An interpretation of main lineaments in the Finnsjön site and its surroundings from aerial-photos on the scale of 1:30 000 is presented in Figure 13. The objective was to complement the lineament interpretation from the topographical map, in particular in the western part of the site, where the these maps have a low resolution.

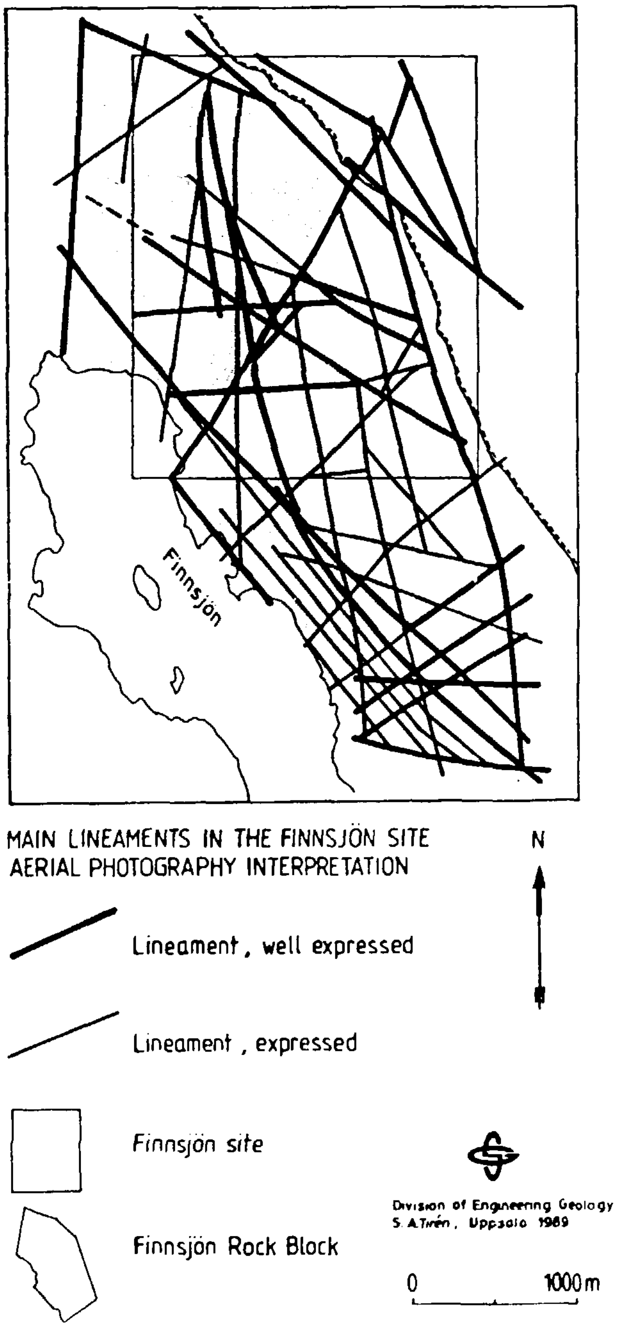

Figure 13. Aerial-photo interpretation of lineaments at the Finnsjön site.

4.5 Minor fracture zones

The fracture zones regarded as being extensive and thus important to the transport of groundwater is discussed separately in Chapter 6. This section concerns minor and less extensive fracture zones mapped on outcrops.

Within the surveyed area, minor N60W shear zones occur at regular intervals, with estimated spacings of 40–400 m. These zones are interpreted to be subvertical to vertical. The most common fracture orientation within the zones is N60W/80–90SW. The fracture frequency varies between 0.5–5 fr/m. The zones are commonly between 1–5 m wide (up to 20 m) and have an extension of several hundred meters or more. Some of the zones appear to have blind terminations. The wall rock is commonly red coloured. The shear zones are often associated with mylonites or sheared amphibolites/–metadolorites. A few restricted minor fracture zones with an NE–orientation have also been mapped.

4.6 Fracture characteristics

Compared with other SKB study sites, the fracture frequency is higher in the Finnsjön site. On the average the frequency, determined on exposed outcrops, is c. 2.9 fr/m (Olkiewicz, 1981). For comparison, the Sternö and Gideå sites display fracture frequencies of c. 0.9 and c. 1.2 fr/m, respectively.

The fracture surveys performed along scan–lines on the ground surface and on cores show the same fracture frequency. This suggests a homogeneous configuration of fractures. The average fracture frequency in the cores from the upper 100 m in the boreholes KFI03, 04 and 05 is 3.0 fr/m (excluding crushed sections). No decrease in fracture frequency with depth (0–600 m) have been observed.

In the northern block (Figure 8) a surface fracture survey indicates a lower fracture frequency, c. 1.5 fr/m. This is also apparent in the cores from boreholes in the northern block. For example, borehole KFI11 display a fracture frequency of about 1 fr/m in the bedrock above Zone 2.

Fracture surveys on outcrops in the Brändan Rock Block have defined three main fracture sets (ordered according to their relative occurrence):

* Northeast (N10–70E) fractures with a steep dip towards SE
* Northwest (N25–80W) fractures with a steep dip towards SW
* Flat lying fractures dipping predominantly to the SW

This configuration of fractures resembles the fracture configuration at Forsmark (SFR1, 1987).

Northeast fractures

Northeast trending fractures are the most frequent occurring fractures. The fracture walls are altered, reddened by hydrothermal fluids. A common infilling in these fractures is iron-rich prehnite, which have, outside this area, been dated to 1,250–1,100 Ma (Wickman et.al. 1983). The northeast fractures often occur en echelon (stepped configuration). This fracture set is interpreted to have been formed by a regional ENE left lateral shearing with a compression component in NNE.

Northwest fractures

The northwest fracture set is older than the northeast fractures and has been formed by a ductile-brittle deformation. This is evident by the common occurring ductile deformation of the wall rock (flexures and mylonites). The northwest fractures are oriented more or less parallel to the foliation in the granodiorite. Regarding the frequency of "open fractures", there is an equal relative occurrence for the two steeply dipping fracture sets, but the northwest fractures are the most extensive.

Flat lying fractures

Flat lying, horizontal to gently dipping fractures are relatively scarce in outcrops. Most fractures dip towards the SW. Some of the southwest dipping fractures show a wall rock alteration similar to the northeast trending fracture set, indicating that these two fracture sets were connected.

4.7 Fracture infillings

The fracture infillings are mostly of hydrothermal origin.
According to Tullborg and Larson (1982) and Tirén (1989), the sequence of fracture infilling, from oldest to youngest, is:

* Epidote and calcite (associated with mylonitic and cataclastic processes).
* Prehnite and calcite/quartz.
* Haematite, laumontite, prismatic calcite and quartz.
* Chlorite and calcite.
* Amorph. Fe^{3+} oxy-hydroxid precipitates (rust)

Most of the fractures are considered to be initiated early in the geologic history and reactivated several times. Geological dating using Rb–Sr indicate ages of 1,600–1,500 million years for epidote and 1,250–1,100 million years for prehnite (Wickman et al., 1983). Late fractures with no evidence of reactivation and lacking hydrothermal minerals are rare.

4.8 Hydraulic properties of the rock mass

An attempt to calculate average hydraulic conductivity for the rock mass, bedrock with fracture zones excluded, and for "fracture zones of well-defined extension" are presented in Carlsson et.al., 1983. They used conductivity data obtained by water injection tests in 3 m sections in boreholes KFI01,02,04,06 and 07. The measurement limit for these measurements were about 10^{-10}–10^{-9} m/s. The tectonic model used for the subdivision between rock mass and fracture zones have not been available for this report. The obtained regression relationships between depth and hydraulic conductivity for the rock mass and for the fracture zones are presented below and in Figure 14. In these relationships both rock mass and fracture zones display an hydraulic conductivity of 10^{-9}–10^{-8} m/s at 500 m depth. Experience from other sites suggest that these values are probably higher than the real values. This is because of possible strong bias due to the high measurement limit for these early measurements.

$K(b) = c \cdot 4.90 \cdot 10^{-6} \cdot z^{-1.30}$ m/s
$K(s) = c \cdot 5.06 \cdot 10^{-3} \cdot z^{-2.15}$ m/s

K(b) = hydraulic conductivity for the rock mass
K(s) = hydraulic conductivity for the fracture zones
c = correlation factor depending on the assumed flow conditions

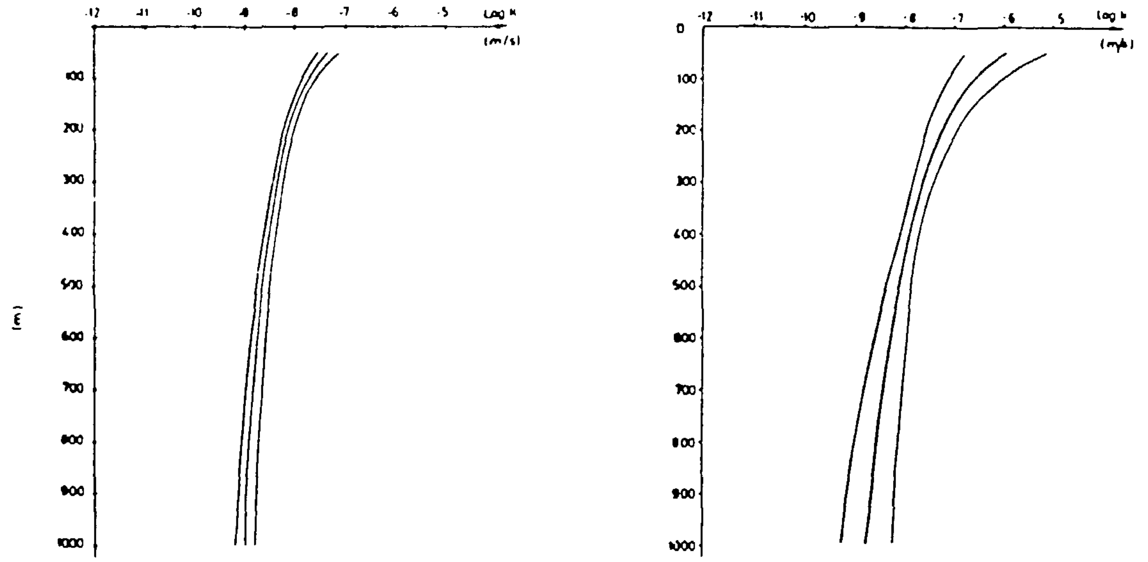

Figure 14. Hydraulic conductivity versus depth from regression analysis for the rock mass (left) and fracture zones (right). (After Carlsson et.al., 1983).

4.9 Rock stress and mechanical conditions

Hydraulic fracturing stress measurements have been performed in the vertical borehole KFI06 at the Finnsjön study site (Bjarnason & Stephansson, 1988). The result shows that the horizontal stresses are greater than the theoretical vertical stress down to c. 500 m depth. This suggest that a thrust faulting stress conditions are prevailing down to this depth. The overall stress magnitudes are in agreement with data from other hydrofracturing measurements in Fennoscandia. The regression analysis of stress magnitudes versus depth are:

$S_v = 0.0265 \cdot z$ (estimated)
$S_h = 2.6 + 0.0237 \cdot z$ $r = 0.92$
$S_{HI} = 6.2 + 0.0416 \cdot z$ $r = 0.85$
$S_{HII} = 2.4 + 0.0412 \cdot z$ $r = 0.89$

S_v = vertical stress (MPa)
S_h = minimum horizontal stress (MPa)
S_{HI} = maximum horizontal stress by the first breakdown method (MPa)
S_{HII} = maximum horizontal stress by the second breakdown method (MPa)
z = depth (m)
r = regression coefficient

The regression analysis indicate that the minimum horizontal stress becomes smaller than the vertical stress at a depth of about 500 m. This would change the stress field to strike–slip conditions. Regression analysis also indicate a small discontinuity in stress magnitude of about 3 MPa over the gently dipping Zone 2. However, this indication is not considered fully reliable (Bjarnason & Stephansson, 1988).

Orientations of vertical hydrofractures show a consistent NW–SE orientation of the maximum horizontal stress. This orientation is almost parallel to the strike of the oldest set of fractures (northwest fractures) and nearly perpendicular to the youngest and most frequent occurring fracture set (northeast fractures). A comparison between the measured stresses field in Forsmark and in Finnsjön shows a general agreement in stress magnitudes and stress orientations.

The mechanical properties of the Finnsjön granodiorite have been determined from laboratory measurements of 12 core samples from depths between 7–444 m (Swan, 1977). The average properties are:

Young's Modules:	83	GPa
Compression Failure stress:	241	MPa
Brazilian Failure stress:	13.5	MPa
Poisson's ratio:	0.20	

Engineering classification using either the strength or the Modules ratio (Deere and Miller, 1966) results in a high quality designation for the Finnsjön granodiorite.

4.10 Thermal gradient and thermal conductivity

The temperature measurements in the subvertical boreholes KFI01, 06 and 07 are presented in Figure 15. From this figure an average thermal gradient of 13 °C/km is calculated. The absolute temperature at 500 m.b.s.l. is 12.3 °C.

Thermal properties for the bedrock at the Finnsjön site has not been determined. However, a rough estimate can be made by using the average quartz content of the rock. Olkiewicz and Arnefors (1981) reports an average quartz content of 30 % for the granodiorite at Finnsjön. This corresponds to values of thermal conductivity between 3.0-3.5 Wm°C (Sundberg et al., 1985).

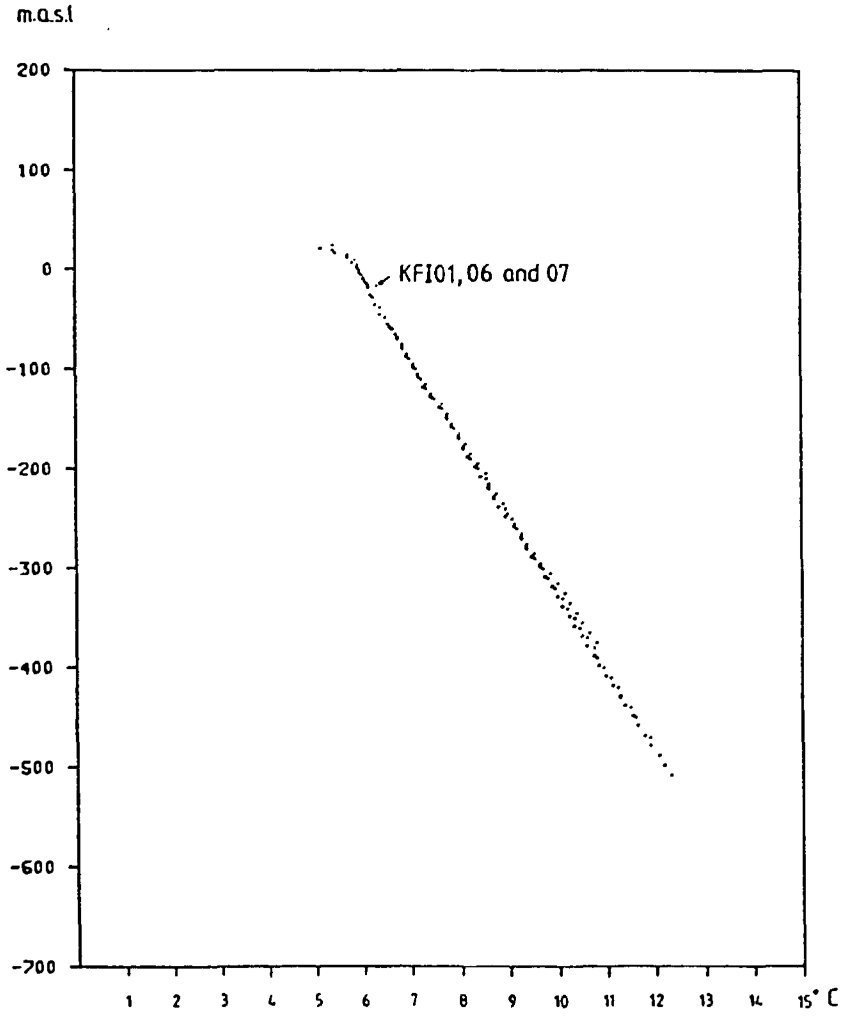

Figure 15. Borehole temperature measurements at the Finnsjön site.

5. SALINE GROUNDWATER AT THE FINNSJÖN SITE AND ITS SURROUNDINGS

Saline groundwater is found both within the Finnsjön site and in its surroundings. This chapter aims to present the distribution of saline wells and other known occurrences of saline waters. Since saline groundwater most likely represent relict groundwater the distribution of saline groundwater in the bedrock indicate areas with stagnant or near-stagnant groundwater.

5.1 Isostatic rebound and marine environment

The load of the last inland ice resulted in a crustal downwarping of c. 500 m in the Finnsjön region. Immediately after deglacation, and as a result of the downwarping, the Finnsjön site was covered by the brackish Yoldia Sea about 9 600 years BP (Eronen, 1988, Figure 16). The continuous crustal uplift closed the connection to the Atlantic and a non-saline water covered the area (Ancylus Lake at 9000 years BP). Between 7500-7000 years BP the sea water become saline (Litorina Sea). This sea was then gradually transformed into the present brackish Baltic Sea. The Finnsjön site was lifted up above the sea level between the years 5000-3000 BP (Almén, 1978). The present crustal rebound at the Finnsjön site is 5.5 mm/year (Ekman, 1987).

Smellie and Wikberg (1989) compared the Finnsjön saline groundwater (see below) with other saline environments. They concluded that the Finnsjön saline water is dominantly marine in origin, probably originated from the Yoldia and Litorina sea waters, but with clear modifications resulting from water/rock interaction processes.

5.2 Saline groundwater in Uppland

Saline groundwater is commonly found in deep bedrock wells in northeast Uppland, where the Finnsjön site is located, Figure 17. It is estimated that at least 10 % of all wells (percussion drilled wells, 50–100 m in depth) in this region encounter saline water (T.Fagerlind, SGU, pers. comm). Unfortunately, only a few of these wells have been reported to the well archive of the Swedish Geological Survey (mainly because saline wells are regarded as failures by the drilling companies). As a result, data regarding saline wells in the vicinity of the Finnsjön site are scarce. However, the abundance of saline wells is the region is clearly shown on the nationwide compilation of saline wells shown in Figure 17. In this compilation wells are regarded saline if the chloride content of the groundwater exceeds 300 mg/l.

There are two underground constructions in the region, the Dannemora Mine and the SFR repository. Both have encountered saline groundwater. In the Dannemora Mine, 17 km south of the Finnsjön site, saline groundwater of

7000 mg/l of chloride occurs at 420 m depth (C. Müllern, SGU, pers. comm, 1990). In the SFR repository, located beneath the Baltic Sea, saline groundwater of up to 6000 mg/l of chloride (Smellie & Wikberg, 1989) have been sampled. For comparison, the chloride content of the brackish water of the Baltic Sea above SFR is 3000–4000 mg/l.

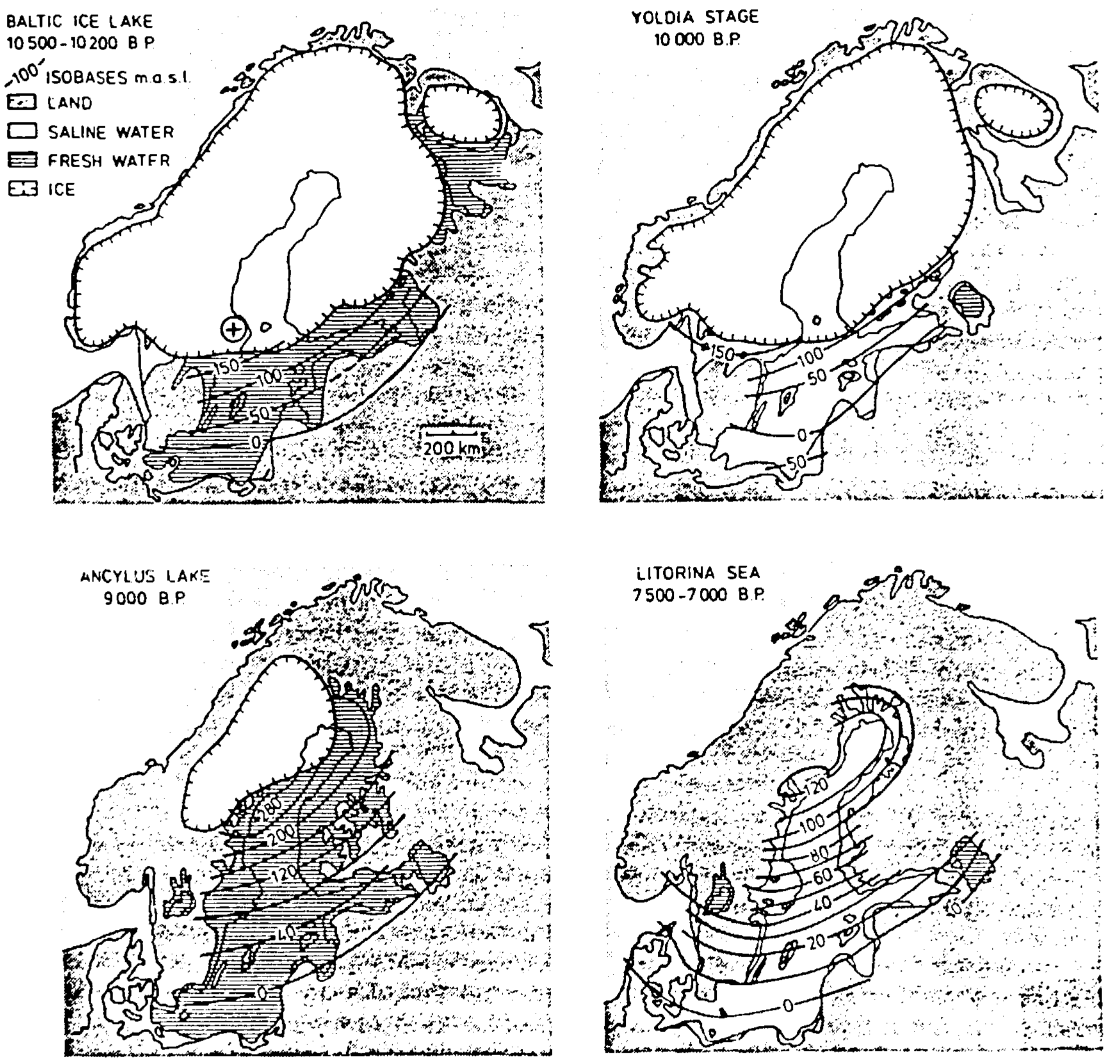

Figure 16. Maps showing four stages of the history of the Baltic Sea (after Eronen, 1988). The Finnsjön site is marked with a ⊕.

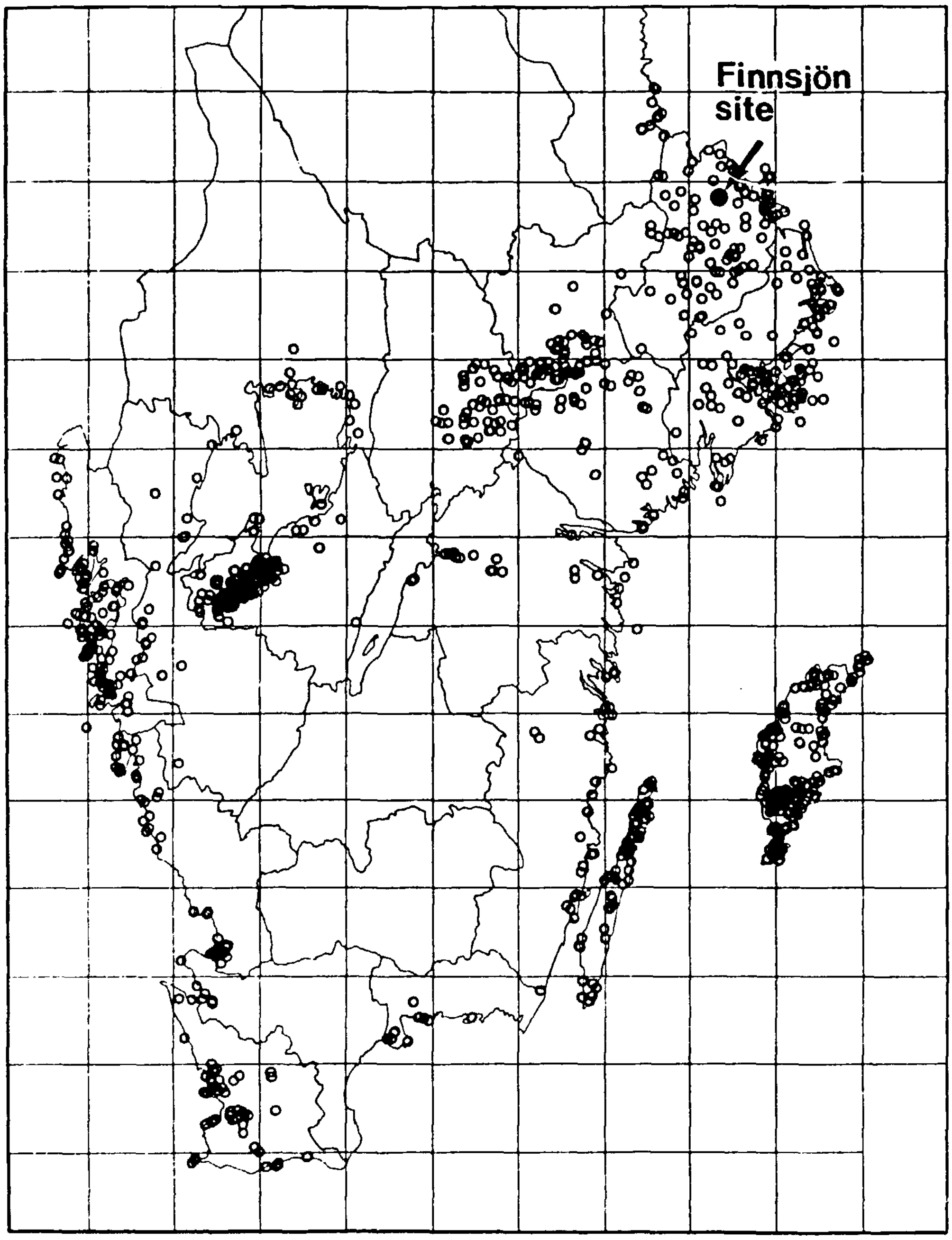

Figure 17. Wells with saline groundwater (after Lindewald, 1985).

5.3 Saline groundwater at the Finnsjön site

The Finnsjön site is located 13 km from the Baltic Sea. Despite the distance to the coast, saline groundwater is found in many boreholes at the site. The total salinity is about 0.8 %, or 5000–6000 mg/l of chloride (Smellie and Wikberg, 1989).

As described earlier, the Finnsjön site can be divided into a northern and a southern rock block, separated by the Brändan fracture zone (Zone 1). In the northern block saline groundwater is found in all 9 boreholes (Figure 9) at depths ranging from 90–300 m. For all boreholes the depths to the saline groundwater coincide with the upper boundary of the gently dipping and hydraulically active fracture zone (Zone 2), (see section 6.3, Figure 23).

In the southern rock block, south of Zone 1, four deep cored boreholes (Figure 9) have been drilled to depths of 500–600 m. Although the borehole tests and groundwater sampling has not been as extensive in this block compared to the northern block, only non-saline waters have been reported from the boreholes.

Outside the site and to the east, the bedrock surface dips eastwards and is covered by a thick bed of glacial clay. The results from two soundings in this area show that the clay is 7–8 m thick. Beneath the clay and overlying the bedrock there is a 1 m layer of moraine (Jacobsson, 1980). The topography of the ground surface is flat and the area is used for farming.

One borehole, KFI08, has been drilled into this area (Figure 22). This borehole is 464 m in length and inclined 60° eastwards. It starts from the southern block, penetrating a N–S and steeply dipping fracture zone (Zone 3, see section 6.4, Figure 18), and continuing under the farmland. Geophysical logging shows that groundwater is non–saline in the upper part of the borehole (southern rock block and Zone 3) but saline (equivalent to 5000 mg/l of chloride) under the farmland.

In summary, saline water is found in the northern block, under the upper part of Zone 2, and under the clay covered areas east of the Finnsjön Rock Block. Stagnant or near–stagnant groundwater conditions can thus be expected in these areas. No such indication of stagnant groundwater have been found in the southern block.

6. INTERPRETED FRACTURE ZONES

6.1 General

This chapter presents interpreted fracture zones at the Finnsjön site. The fracture zones are interpreted as extensive, either intersecting the Finnsjön Rock Block or constitute boundaries to the block. The geometrical data for all fracture zones are summarized in Table 2. Minor, less extensive fracture zones, are discussed in section 4.5.

Table 2. Geometrical data for interpreted fracture zones.

Zone	Strike	Dip	Length (km)	Width (m)
1	N30E	75SE	5	20
2	N28W	16SW	1.5	100
3	N15W	80W	5	50
4	N50W	65SW	1	10
5	N50W	60SW	5	5
6	N55-65W	60SW	2	5
7	N55W	60SW	2	5
8	N50W	90	3	5
9	N10W	15W	2	50
10	NW	85SW	2.5	5
11	N5W	35W	2	100
12	N-S	90	6	25
13	N30E	75SE	7	20
14	NW	90	>50	100

The intersections between boreholes and fracture zones is presented in Table 3, both as borehole length and as depth below ground surface. The depths below ground surface are calculated from borehole deviation data in SKB database GEOTAB.

Table 3. Location of fracture zones in boreholes.

Fracture zone	Borehole	Borehole length (m)	Depth below ground surface (m)
1	KFI05	10–48	8–38
	KFI10	75–105	57–80
2	KFI05	166–305	124–235
	KFI06	201–305	201–305
	KFI07	295–380	295–380
	KFI09	130–212	112–183
	KFI10	152–256*	116–193*
	KFI11	221–338	221–338
	BFI01	240–365	238–362
	BFI02	204–289*	204–289*
	HFI01	105–125*	105–125*
3	KFI08	20–150	17–129
5	KFI05	485–498	370–379
	KFI06	554–557	554–557
	KFI09	212–216	184–187
6	KFI07	530–537	527–535
9	KFI07	109–154	109–154
10	KFI03	57–62	42–48
11	KFI01	332–436	332–436
	KFI03	107–245	82–188
	KFI04	368–440	365–436
	KFI08	20–125	17–107

*not fully penetrated

6.2 Reliability of interpreted zones

The general control of the geologic conditions of the northern block is far better known compared to the southern block (Figure 8), due to the detailed studies that has been conducted within the fracture zone project (Chapter 1) in the southeastern part of the northern block. This difference also implies a general higher reliability of interpreted fracture zones in the northern block compared to the southern block.

Apart from this general difference in reliability betweeen the two blocks, the only zones that can be regarded as well established, with respect to location and character, are Zone 1 and Zone 2 (in areas where these zones are intersected by boreholes). Other interpreted fracture zones must be regarded as more or less uncertain. For zones interpreted from lineaments, there are normally no information regarding degree of fracturing nor the dip and even if a single borehole intersects a zone there might be several alternative interpretations regarding its orientation.

To reduce these uncertainties and also to test the model, direct comparison between drill cores would be one way to improve the reliability of the interpretations. However, this is not possible for fracture zones interpreted from lineaments only. In this case, new boreholes or trenches across the lineaments, would be required to increase the reliability. It should also be noted that further work on detailed correlation between surface and borehole data would probably identify additional fracture zones.

In spite of the above discussed uncertainties and differences in knowledge between different blocks, a tentative tectonic model of the Finnsjön site is presented below. The model is based on interpreted lineaments and, where available, on core logs and geophysical logs. If several alternatives regarding dip or width have been possible, the most probable alternative have been selected. The interpreted fracture zones are presented in a generalized map of the Finnsjön Rock Block and its surroundings, Figure 18. Detailed maps of interpreted fracture zones at the ground surface and at 500 m depth are presented in Figures 19 and 20.

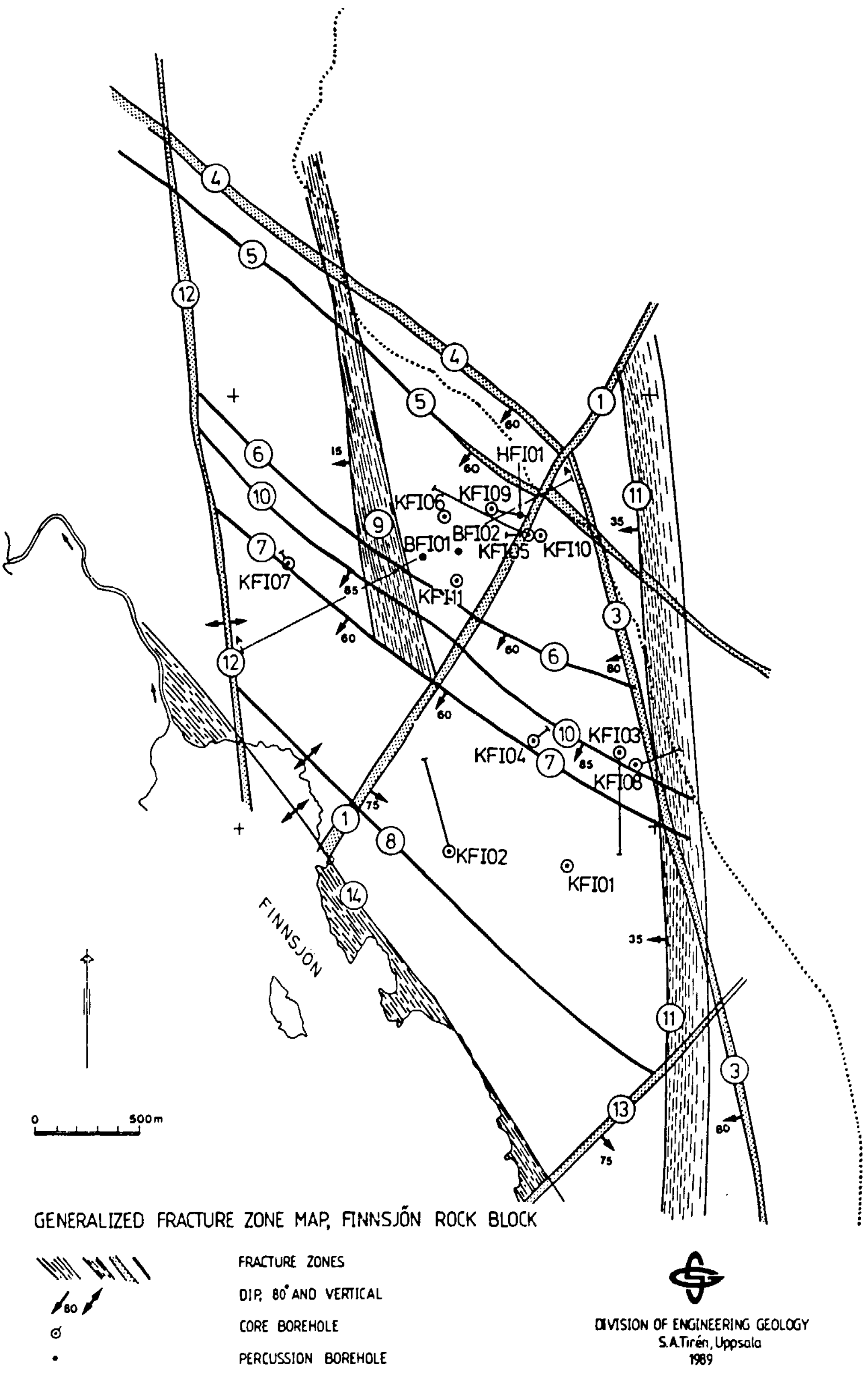

Figure 18. Generalized map of fracture zones at the Finnsjön Rock Block.

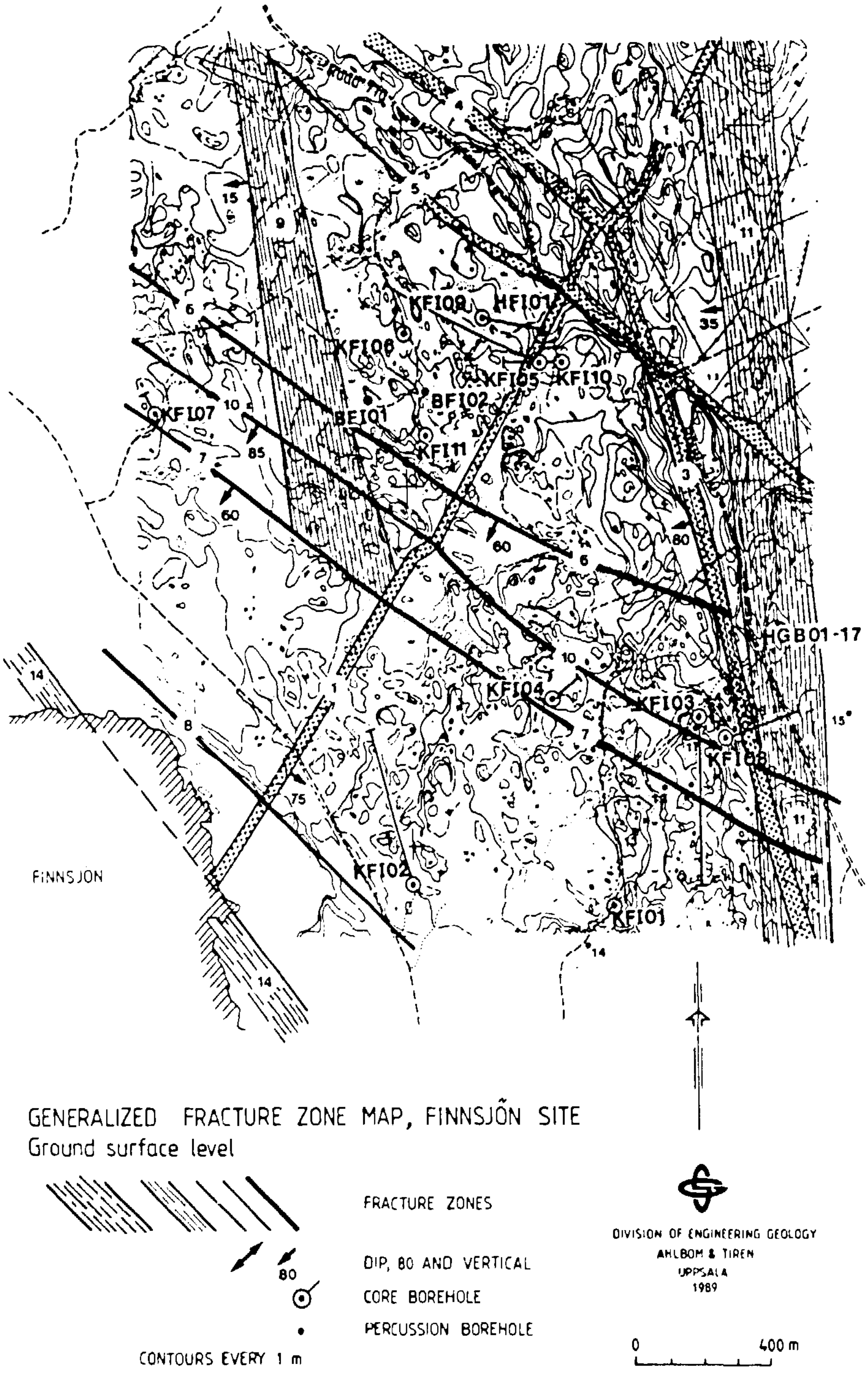

Figure 19. Generalized map of fracture zones at the Finnsjön site.

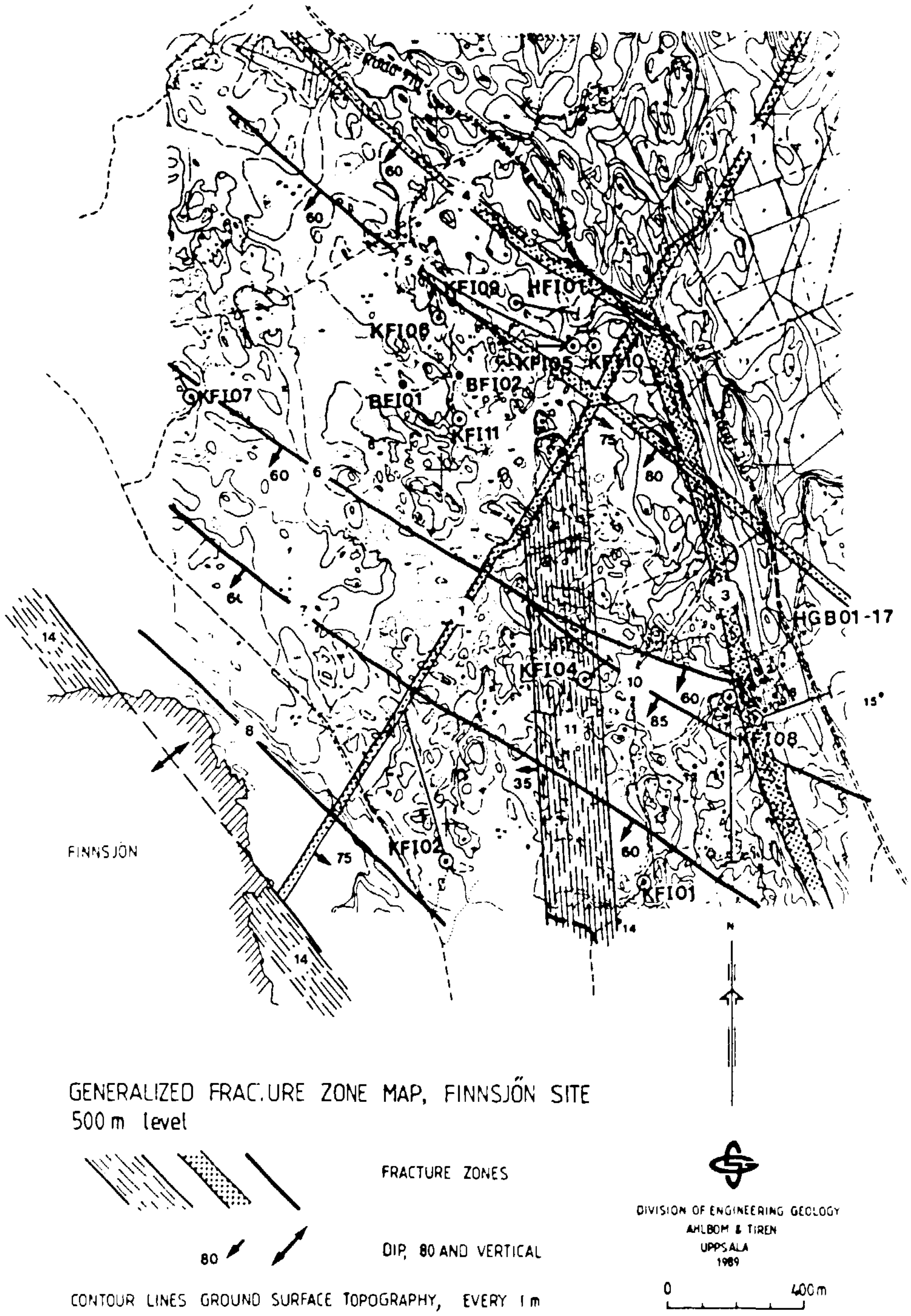

Figure 20. Generalized map of fracture zones at the Finnsjön site at a depth of 500 m.

6.3 Zone 1, the Brändan fracture zone

General

The most prominent lineament transecting the Finnsjön Rock Block is caused by the Brändan fracture zone (B in Figure 10). The zone is oriented N30E/75SE and with a length of c. 5 km. The width is estimated to 20 m. In addition to its lineament expression, the zone is also indicated on geophysical maps and identified in the cores from borehole KFI05 and KFI10.

Surface expression

The surface expression of the Brändan fracture zone is an open, about 5–50 m wide, peat covered gully. Fracture surveys in the eastern part of the Finnsjön site indicate that the Brändan fracture zone constitute a border between rock blocks of different tectonic character. The rock block south of the Brändan fracture zone is characterized by northeast trending fractures with pink coatings of laumontite and haematite. Fractures of this type is rare in the northern rock block. The different tectonic character between the blocks indicate that faulting has occurred on the Brändan fracture zone. The degree of fracturing in the surrounding outcrops does not increase significantly when approaching the zone.

The difference in tectonic character is also indicated by a ground resistivity survey (Ahlbom et al., 1986) in which the Brändan fracture zone constitute a boundary between a fractured part of the southern rock block (in the area where boreholes KFI05 and KFI10 are located) and a low-fractured northern rock block.

Geologic character

Two cored boreholes, KFI05 and KFI10, intersects the Brändan zone. The cores from the Brändan zone are altered and red coloured. The fracture frequency in the zone is high, ranging between 8–20 fr/m, with the highest values along the western side of the zone. Characteristic fracture infillings are haematite and asphaltite.

Hydraulic character

Water injection tests in the Brändan fracture zone have been carried out in borehole KFI10. This borehole penetrates, within a close distance, both the Brändan zone and the upper part of Zone 2. This is reflected in a high hydraulic conductivity for all 20 m sections for the total length of the borehole (256 m). However, an increase of the conductivity is measured at the intersection with the Brändan fracture zone. Here, the conductivity values ranges between $1 \cdot 10^{-6}$ m/s and $5 \cdot 10^{-5}$ m/s at vertical depths between 57 and 76 m. The hydraulic conductivity of the country rock is 5–10 times lower.

6.4 Zone 2, the gently dipping fracture zone

General

The Zone 2 has been thoroughly investigated during the fracture zone project (Ahlbom & Smellie, 1989). A great amount of data is therefore available and is summarized below. Zone 2 is oriented N28W/16SW, c. 100 m wide and with a estimated length of c. 1.5 km.

Zone 2 was formed more than 1600–1700 million years ago as a some hundred meters wide ductile shear zone at a depth of c. 10 km. Zone 2 is a product of repeated shear movement along the zone. The deformation has resulted in the frequent occurrence of mylonites, cataclastic rocks, and a high frequency of sealed fractures.

Surface expression

Zone 2 has not been found to outcrop within the Finnsjön Rock Block.

Geologic character

Zone 2, Figure 21, is defined in eight boreholes located within an area of c. 500 m x 500 m in the eastern part of the northern block (north of Zone 1). In the eastern part of the northern block the upper boundary of Zone 2 is almost planar, oriented in N28W/16W, and located in boreholes between 100 to 240 m below the ground surface. The location of the lower boundary is less distinct. In general, Zone 2 is interpreted to have a width of about 100 m. In the western part of the northern block the upper boundary of Zone 2 is interpreted to occur in borehole KFI07 at a depth of 295 m. Since this is somewhat shallower than expected, Zone 2 can not be planar between the eastern and western parts of the northern block (cf. Figure 21). There is no indication in the boreholes in the southern block that Zone 2 extends across the Brändan fracture zone, into the southern block.

Although Zone 2 is expressed as an c. 100 m wide more or less altered zone, the fracture frequency is generally low within Zone 2, except for two or three fractured sections in each borehole. These sections are narrow, 2–30 m wide (often 2–5 m wide) and are mainly located at the upper and lower boundaries of the zone. The hydraulically conductive parts of these sections are even more narrow, in some boreholes the widths of these parts are in the order of 0.5–1 m. Narrow fractured parts in the central part of the zone also occur in some boreholes.

Late reactivation of Zone 2 seems to occur preferentially along the upper boundary of the zone. The average fracture frequency for Zone 2 is 5 fr/m. An interpretation of the fracture configuration within Zone 2 is presented in Figure 21.

The fracture characteristics of Zone 2 resemble a compound fault (Martel, 1990), cf. Figure 22, where some of the early fractures have been reactivated in a late tectonic phase to develop a compound fault structure. Characteristic for such a structure is a stepwise lateral extension of the zone. This stepwise continuation can explain why Zone 2 cannot be followed as a continuous planar surface between the eastern and the western part of the northern block. An alternative explanation for the non–continuous planar lateral extension is displacement of Zone 2 on late formed faults.

The bedrock above the Zone 2 is low–fractured and unaltered, while the bedrock below the zone is more deformed with inliners of fault rocks and with a general higher degree of fracturing.

To obtain structural information of Zone 2, and possible additional subhorizontal fracture zones at greater depths, a reflection seismic survey was performed in the northern part of the Finnsjön Rock Block (Jensen and Lindgren, 1987). The survey was not successful in detecting Zone 2, probably because of low reflection coefficient. Furthermore, no structural information could be obtained of the bedrock below the zone until a depth of c. 1500 m. Between 1500–3000 m depth a broad reflecting band indicate a complex reflecting zone. In contrast to Zone 2, the steeply dipping Zone 1 is clearly identified on a number of shot sections.

A brief study has been made on possible late tectonic movement in Zone 2. This is important since if such movement has occurred then it might not be possible to extrapolate surface data across Zone 2. Late movements has been studied by interpolating fracture zones or dykes identified in boreholes or on the ground surface across Zone 2. Furthermore, the borehole radar maps have been used to study the continuity of single structures from the block above to the block below Zone 2.

The result indicate that there has been none or only small movements along Zone 2 after the ductile deformation has ceased. This is indicated by three observations. A N30E trending aplite dyke, which is traceable for more than 500 m, is identified in borehole KFI09 (above Zone 2) and in borehole KFI05 (below Zone 2). The locations of the dyke, at the surface and in the boreholes, can be plotted on a continuous plane, indicating that no significant tectonic movement in Zone 2 has occurred since emplacement of the dyke.

Borehole radar maps of boreholes KFI05 and KFI07 both show a strong reflector parallel to the boreholes. Both these reflectors are interpreted to continue across Zone 2, indicating no or only small tectonic movement. In borehole KFI07, Figure 23, there is a small displacement of the reflector of about 5–10 m, but it is not clarified whether this displacement has occurred by movements in Zone 2 or in a subvertical fracture zone. The reflector in borehole KFI07 is identified as a N60W–trending shear zone containing amfibolite lenses.

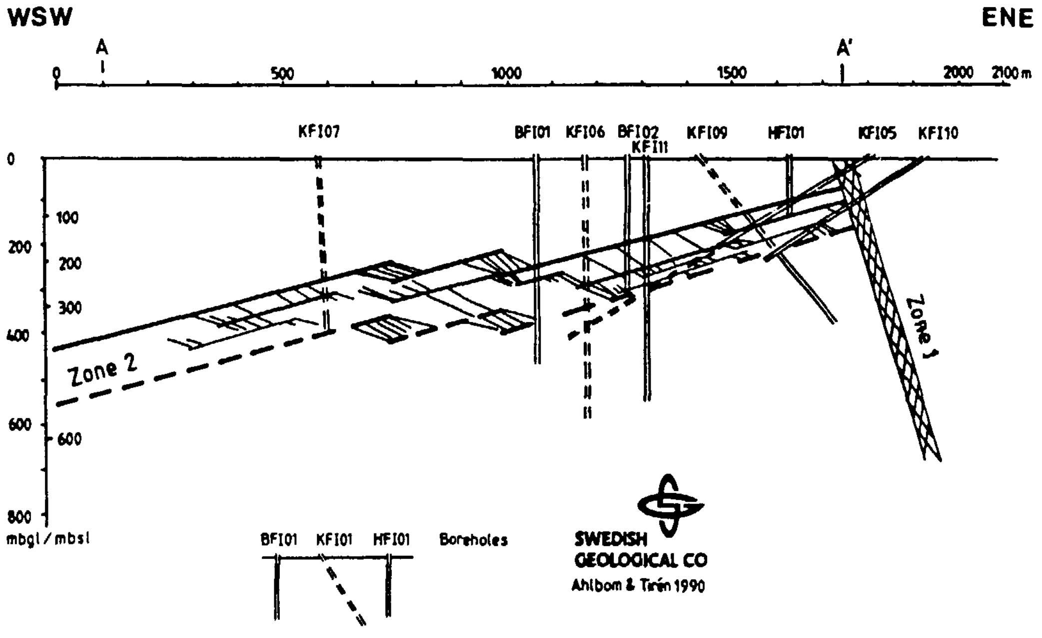

Figure 21. Schematic illustration of Zone 2. Boreholes drawn with full lines are located in front of the profile, while boreholes with dashed lines are located behind the profile. Location of the profile is shown in Figure 18.

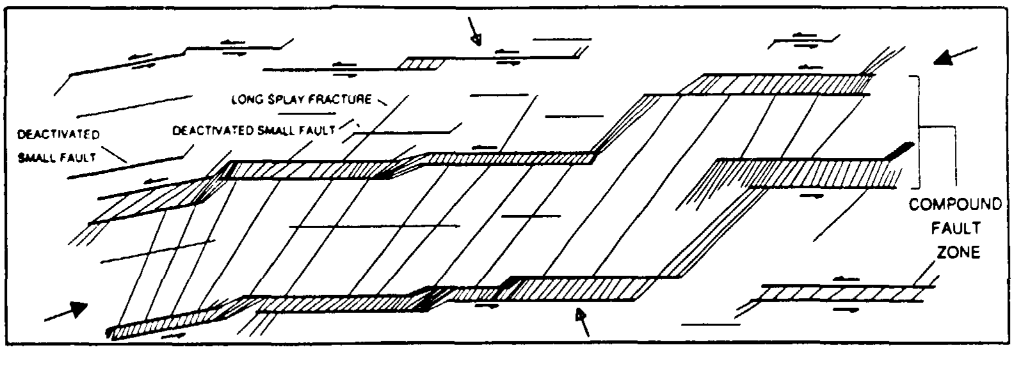

Figure 22. Schematic illustration of a compound fault zone in Bear Creek area (after Martel, 1990).

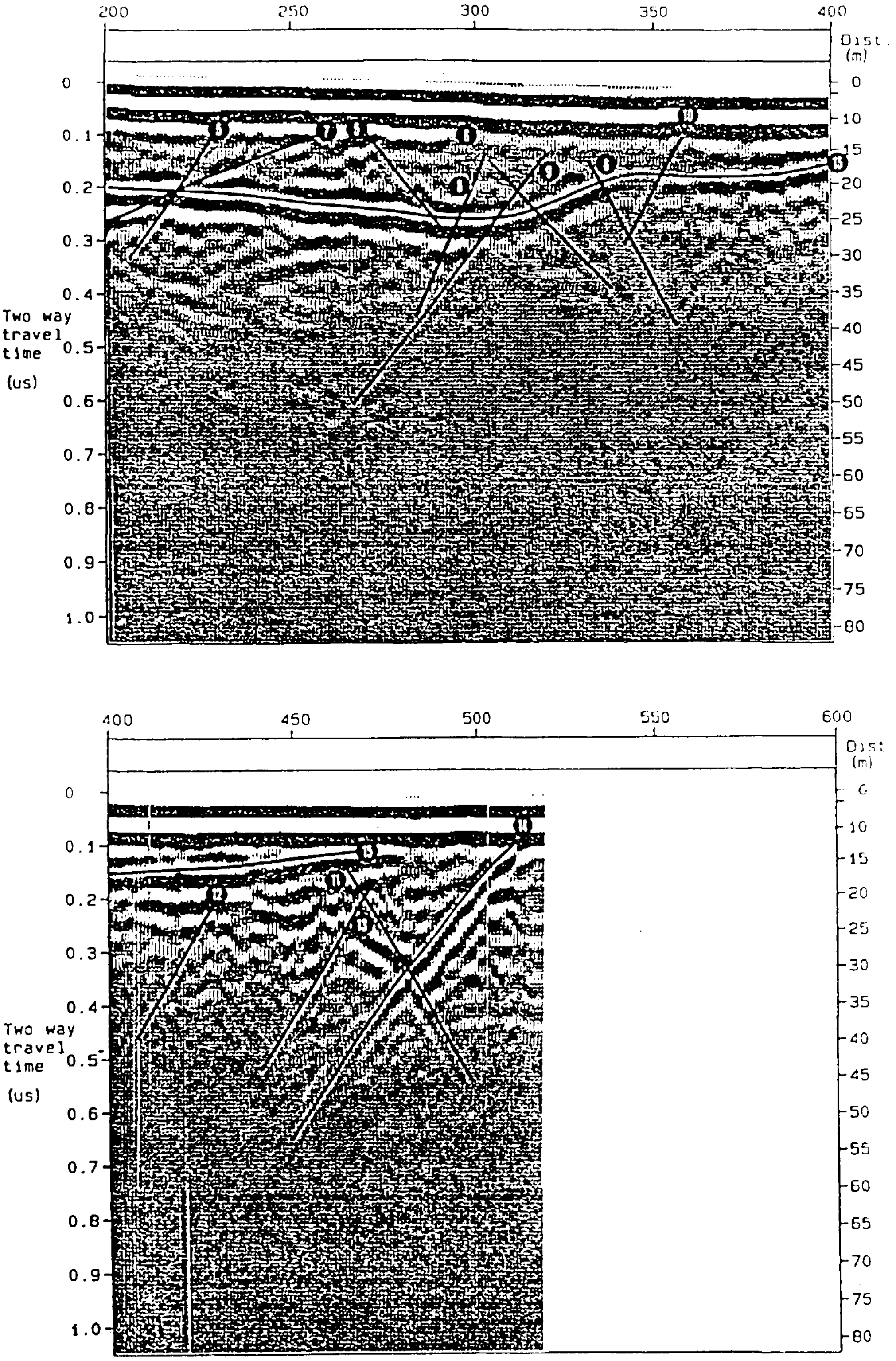

Figure 23. Radar measurements of borehole KFI07. Note the strong reflector running parallel to the borehole. A small displacement of 5–10 m can be observed at the intersection with Zone 2 (300–380 m).

In conclusion, the study indicates that only insignificant movements have occurred on Zone 2 after the ductile deformation have ceased. This result may allow the extrapolation of later formed fracture zones and dykes across the Zone 2. However, before this can be stated conclusively more studies of possible late reactivation of Zone 2 must be made.

Hydraulic character

There is a great number of hydraulic tests available from the gently dipping Zone 2 and its surrounding bedrock. A summary of these tests is presented below.

The water injection tests show for most boreholes a general decrease in hydraulic conductivity towards depth for the bedrock above Zone 2. This decrease is interrupted by the zone, where the hydraulic conductivity increases by one to four orders of magnitude to values between 10^{-6} – 10^{-5} m/s (measured in 20 m sections). Using much smaller packer intervals, 2.0 m and 0.11 m respectively, the latter only in borehole BFI02, indicate that the most conductive parts of Zone 2 merely consist of a few very narrow subzones with a width of only about 0.5 m. The uppermost of these subzones, which coincides with the upper boundary of Zone 2, is highly water conductive (10^{-4} m/s). This subzone can be correlated between all boreholes in the northern block.

Towards the bottom of Zone 2 there are several "narrow subzones" with very high hydraulic conductivity (more than 10^{-4} m/s measured in 20 m packed-off sections). These conductive subzones are separated by bedrock with low hydraulic conductivity. Below the zone the conductivity is in general low (10^{-10}–10^{-8} m/s) with several minor sections with high hydraulic conductivity (10^{-7}–10^{-6} m/s). Given the narrow widths of the subzones, the hydraulic properties of Zone 2 should preferably be expressed in terms of transmissivity rather than average hydraulic conductivity of longer test sections. The transmissivity of each subzone has been estimated to $1–4 \cdot 10^{-3}$ m^2/s.

Registration of the groundwater heads (Gustafsson and Andersson, in Ahlbom & Smellie, 1989) shows that in the western and deeper part of the Zone 2, groundwater from the upper bedrock infiltrates into the upper, high conductive, part of the zone. This water is then discharged within the zone to its eastern part where the groundwater head is higher than in the overlaying bedrock. This flow condition have been proved by a tracer test under natural hydraulic gradient between the boreholes KFI11 in the western part and HFI01 in the eastern part of the Zone 2. The distance between these boreholes is c. 400 m and the tracer was transported this distance in slightly less than one month. The fracture conductivity of the upper part of Zone 2, calculated from this tracer test, is between $3 \cdot 10^{-2}$–$2 \cdot 10^{-1}$ m/s.

The groundwater flow has also been measured in situ in two boreholes by a borehole point dilution probe (Gustavsson, 1986). The results showed that the natural groundwater flow in Zone 2 is concentrated along its upper boundary; the obtained values were 67 and 90 $m^3/m^2 \cdot$year, respectively. In the lower parts of Zone 2, no groundwater flow was measured in spite of high hydraulic conductivity in the surrounding bedrock. This indicates that no hydraulic gradient, is present below the upper boundary of Zone 2. The high natural groundwater flow at the upper part of Zone 2 implies that in addition to groundwater derived from infiltration through the overlying bedrock there is a component of regional groundwater flow (Ahlbom and Smellie, 1989).

As discussed in Chapter 5, stagnant groundwater conditions is indicated by the occurrence of saline groundwater in all boreholes below the upper boundary of Zone 2. The salinity increases from fresh water above Zone 2 to about 0.8% of total salinity (5500 mg/l of chloride), below the upper boundary of Zone 2. The salinity is remained high below the zone.

A schematic model showing the main structural and hydraulic characteristics of Zone 2 is presented in Figure 24. In the model the main part of the groundwater transport is assumed to take place in the upper, most conductive part of the zone. Below Zone 2 there may be some circulation of saline water towards the zone, as indicated in the figure, but the flow-rate is probably very low when compared to the fresh water above the zone.

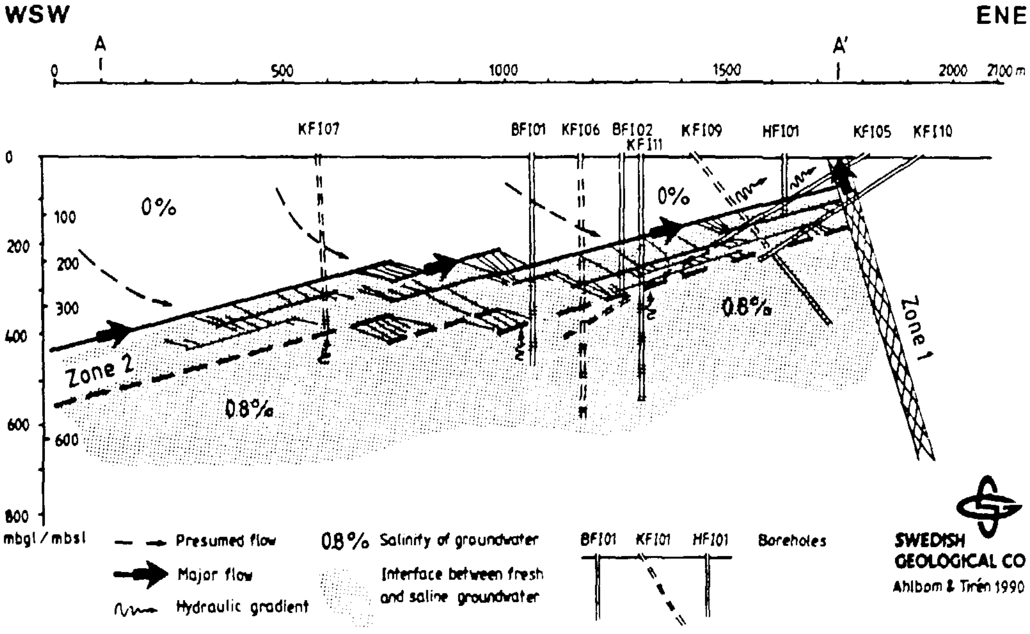

Figure 24. Tentative model of groundwater flow at Zone 2.

6.5 Zone 3, the Gåvastbo fracture zone

General

The N15W/80W trending Zone 3 delimits the Finnsjön Rock Block to the east. The zone is at least 5 km long and c. 50 m wide. Zone 3 is penetrated by one cored borehole, KFI08.

Surface expression

Zone 3 is morphologically expressed as a depression floored by moraine, then clay and on top a thin layer of peat. Soundings indicate a depth of the sediments in the order of 5 m.

Geologic character

The core mapping of KFI08 has not been reported. However, a brief look a the worksheets for the core logs show the following characteristics for the Gåvastbo fracture zone. Zone 3 is highly fractured with mylonized and brecciated sections. Common fracture minerals are epidote and chlorite. The amount of aplite and pegmatite dykes increases towards the end of borehole, indicating that the contact between the granodiorite and the young granite, east of Gåvastbo fracture zone, is close.

The core mapping, geophysical logging and radar measurements suggest that this fracture zone is subvertical, dipping 80–85 degrees towards the west. However, as discussed under Zone 11 (see below) the dip can also be more gently c. 30–40° to the west. Until more studies have been made the steeply dipping alternative is selected for Zone 3.

The geophysical logs indicate a strongly fractured bedrock down c. 120 m borehole length corresponding to a width of the zone of about 60 m. However, since it is possible that this fractured section also includes Zone 11 (see below), the width estimate is uncertain.

Hydraulic character

Water injection tests in 3 m sections have been performed in borehole KFI08 from 43 m to the end of the borehole (458 m). The results have not been evaluated and reported but available data suggest values of hydraulic conductivity between 10^{-6} m/s to 10^{-7} m/s down to 225 m borehole length, corresponding to c. 200 m depth. Below this depth the hydraulic conductivity is commonly between 10^{-9} m/s to 10^{-10} m/s.

6.6 Fracture zones 4, 5, 6, 7, 8 and 10

General

This section presents the northwest trending fracture zones. Zone 4 is situated outside the Finnsjön Rock Block, while the others transect the block.

Zone 4

Zone 4 is defined by a c. 1 km long N50W trending lineament indicated on topographical maps and aerial-photos. No borehole information exist regarding this zone. However, as this zone is situated close to Zone 5 and has the same orientation, the same dip as Zone 5 (60 degrees towards SW) is suggested. Assumed width is 10 m.

Zone 5

This zone (Norrskogen lineament, Figures 8 and 18) is traceable for c. 5 km and has a northwesterly orientation (N50W). Zone 5 delimits the Finnsjön Rock Block to the northeast. It is well expressed as a lineament on both aerial-photos and on topographical maps. A dip of 60 degrees towards the southwest is suggested for this zone. If so, the Zone 5 coincides with weathered and fractured sections in the boreholes KFI05, KFI06 and KFI09 at 493 m, 555 m and 214 m, respectively (borehole length). This interpretation will result in a width of the zone of, at least, 2–6 m. The hydraulic conductivity of Zone 5 decreases with depth from $2 \cdot 10^{-5}$ m/s to $9 \cdot 10^{-8}$ m/s, at depths of 185 m to 555 m.

The depths of intersection and the hydraulic conductivity of the Zone 5 is presented in Table 4. In this table the results of 3-m sections for boreholes KFI05 and KFI06 are normalized to 20-m sections. The tabulated values indicate a decrease in hydraulic conductivity with depth for Zone 5.

Table 4. Zone 5; depth of intersections and hydraulic conductivities (20 m sections) in boreholes.

Borehole	Intersection with Zone 5*		Hydraulic conductivity
	Borehole length	Depth	
KFI09	214 m	185 m	$2 \cdot 10^{-5}$ m/s
KFI05	493 m	378 m	$3 \cdot 10^{-7}$ m/s
KFI06	555 m	555 m	$9 \cdot 10^{-8}$ m/s

*center of zone

Zone 6

This smoothly curved northwesterly (N55-65W) trending fracture zone, c. 2 km long, is only poorly expressed on aerial-photos and on topographical maps. However, ground geophysical measurements indicates that the southeastern part of the zone constitutes a boundary between a fractured rock, to the north, and low fractured rock to the south of the zone. As this zone has the same trend as Zone 5, a dip of 60 degrees towards SW is suggested. With the assumed dip Zone 6 will intersect borehole KFI07 at c. 500 m. At this depth the core of KFI07 is strongly fractured, thus supporting the suggested dip. Estimated width is 5 m.

Zone 7

Zone 7 trends N55W and is traceable for more than 2 km. It is well expressed on aerial-photos and topographical maps. No borehole information exist regarding this lineament. In accordance with earlier presented northwest trending fracture zones, a dip of 60 degrees towards SW is suggested for Zone 7. Assumed width is 5 m.

Zone 8

Zone 8 trends N50W and is more than 3 km long. It is apparent as a distinct lineament in the southwestern part of the Finnsjön Rock Block. No borehole information is available. A vertical dip is assumed for this zone due to the closeness and probable affiliation to the vertical, wide and extensive Zone 14 (see below). A width of 5 m is assumed for Zone 8.

Zone 10

Zone 10 have northwesterly trend. It is traceable for more than 2.5 km and poor to well expressed in the detailed topographical map. It is observed in the field, north of its intersection with Zone 1, as increased fracture frequency in the surrounding outcrops to a 10 wide gully. Zone 10 is curved in the southern block. Field observations and indications in borehole KFI03 (57-62 m) indicate a vertical to steep westerly dip (85°). Estimated width is 5 m.

6.7 Fracture zones 9 and 11

General

Fracture zones 9 and 10 represent, together with Zone 2, gently dipping fracture zones within the Finnsjön area.

Zone 9

Zone 9 represent a 200–300 m wide N10W trending lineament of low topographical relief in a c. 2 km long stripe of peat and moraine. No conclusive data exist regarding the dip, width and character of Zone 9.

There are two alternative interpretations regarding the orientation of Zone 9. In Ahlbom et al. (1986), two steeply dipping fracture zones of lower order was interpreted to be located at the east and west margin of Zone 9. In Andersson et al. (1989), Zone 9 is interpreted as a gently inclined zone, dipping 15 degrees, which comprises gently dipping fractures, less than 5 fractures/m. The interpretation was based on fracture studies on outcrops and in borehole KFI07. The latter interpretation, with a gently dipping fracture zone, is in this report regarded as the most probable. In this case Zone 9 will intersect borehole KFI07 at c. 100–150 m. Since no significant increase in hydraulic conductivity have been measured in this section, Zone 9 has probably no or only limited influence on the groundwater flow conditions.

Zone 11

The existence of a N5W, gently and westerly dipping (35°) fracture zone in the southern block is indicated by geological and geophysical data from boreholes KFI01, KFI03 and KFI08. Combining data from these boreholes with core mapping of KFI04, it is possible to define a c. 100 m wide fracture zone. The available information does not allow an accurate determination of strike and dip, but generally the strike is estimated north–south and the dip between 30–40° to the west. The calculated outcropping of the zone is shown in Figures 18 and 19. As can be seen in Figure 19 the calculated outcropping coincides well with a 2 km long topographic low area.

The existence of a gently dipping fracture zone in boreholes KFI01 and KFI04 is supported by gentle–subhorizontal dipping fractures in the drill cores (similar as for Zone 2). Still, the existence of this zone is uncertain and should be tested, eg. by direct comparison between drill cores from the four boreholes that penetrates the Zone 11.

Tentatively interpreted intersections of Zone 11 in the four boreholes are presented in Table 5 together with hydraulic conductivity ranges.

Table 5. Depth of intersection and hydraulic conductivity (2 or 3 m sections) of Zone 11.

Borehole	Intersection with Zone 11 Borehole length	Approx. Depth	Hydraulic conductivity
KFI08	20–125 m	17–108 m	10^{-5} - 10^{-9} m/s
KFI03	107–275 m	82–211 m	10^{-4} - 10^{-9} m/s
KFI01	332–436 m	332–436 m	10^{-7} - 10^{-9} m/s
KFI04	368–440 m	362–433 m	10^{-4} - 10^{-9} m/s

As mentioned in section 6.5, borehole KFI08 intersects Zone 11 at the same location as Zone 3. This could possibly imply that the earlier interpretation of a subvertical Zone 3 could be wrong and instead Zone 3 is the same as Zone 11. The limited data available (no reported and evaluated core log of borehole KFI08 exist) does not allow any further elaboration on this possibility.

6.8 Fracture zones 12, 13, 14

General

Fracture zones 12, 13 and 14 constitute, together with the earlier described Zones 3 and 5, the boundaries of the Finnsjön Rock Block.

Zone 12

There are no borehole data available for this c. 6 km long and north–south trending fracture zone, delimiting the Finnsjön Rock Block to the west (outside the Finnsjön site, Figures 8 and 18). However, as a first attempt this zone are given a vertical dip and the same characteristics as Zone 3. Assumed width is 25 m.

Zone 13

There are no borehole data available for this c. 7 km long and northeast (N30E) trending fracture zone, delimiting the Finnsjön Rock Block to the south (outside the Finnsjön site, Figures 8 and 18). However, as a first attempt this zone are given the same characteristics as Zone 1 (a dip of 75° to SE and a width of 20 m).

Zone 14

Ground surface and borehole data are lacking for the wide and regionally extensive (>50 km) northwest trending zone delimiting the Finnsjön Rock Block in the southwestern part. However, as this zone have the same strike as the Singö fault, and are interpreted to be related genetically, data from this fault could be used as a first assumption. In this case, a width of 100 m and a vertical dip should be denoted for this zone. Using values from the Singö fault, an hydraulic conductivity of about 10^{-7} m/s to 10^{-6} m/s is expected for the upper 100 m of the zone.

7. DISCUSSION

The geologic and tectonic interpretation in different scales have identified a rock block, the Finnsjön Rock Block, in which the Finnsjön site is located. This block is situated in a regional WNW trending shear belt. Since also the SFR site is interpreted to be located within this belt, it is probable that both sites share the same regional tectonic history. This is also suggested by the similarities between SFR and Finnsjön in fracture orientation, state of stress and the existence of subhorizontal fracture zones at both sites. To some extent, the SFR data could therefore be used as rough estimates regarding geologic and hydrogeologic properties of features at the Finnsjön site.

The fracture zones at the Finnsjön site and its surroundings has been interpreted from available data. In the northern block the tectonic characteristics are well documented by the studies performed within the fracture zone project, while only a limited information regarding fracture zones have been reported from the southern block. To extend the structural information from the northern to the southern block lineament analysis have been made and tested by available borehole data. Still, most of the interpreted fracture zones in the southern block of the Finnsjön site and its surroundings can not be regarded as well established.

Bearing in mind the uncertainties discussed above, the tectonic model of the Finnsjön site and its surroundings includes the following main characteristics.

The Finnsjön Rock Block is divided in two second order blocks, the northern and the southern blocks, separated by a northeasterly trending fracture zone (Zone 1). Within these blocks third order blocks exists. The boundaries of the third order blocks are northwesterly trending fracture zones, dipping mainly 60 degrees towards southwest. The fracture zones within the Finnsjön Rock Block are known or interpreted to have a width of 5–100 m.

In the northern block the wide and gently dipping Zone 2 constitute a boundary between an upper and low-fractured bedrock and a more fractured bedrock below Zone 2. The groundwater in the upper block consist of fresh water, while the groundwater in the lower block is stagnant, consisting of relict saline water. An additional gently dipping and equally wide fracture zone is indicated in the southern block.

The difference in the general knowledge between the rock blocks south and north of the Brändan fracture zone (Zone 1) suggest that, for the purpose of the safety assessment of SKB-91, the generic repository should be located in the northern block. The stagnant groundwater conditions below Zone 2 is also a factor that favours the location of the generic repository in this block.

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